CANADA–SASKATCHEWAN MINERAL DEVELOPMENT AGREEMENT

Canada

Saskatchewan

IMPROVED UNDERSTANDING & PREDICTABILITY OF SALT ANOMALIES IN POTASH MINES PHASE I

By: The University of Saskatchewan

For: CANMET, Energy Mines & Resources Canada

Contract # 55SS.23440-7-9187

This study was funded by CANMET under the terms of the Canada/Saskatchewan Mineral Development Agreement 1985/90.

DSS Contract #: 23440.7-9187/01-SS
Science Contracting Officer: R. Findlayson
CANMET Scientific Authority: Dr. S. Vongpaisal
CANMET Project #: 140905
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61 pp

MICROMEDIA

RESEARCH & DEVELOPMENT IN SASKATCHEWAN POTASH MINES

IMPROVED UNDERSTANDING AND PREDICTABILITY OF SALT ANOMALIES IN POTASH MINES

FINAL REPORT - PHASE I

Prepared for:

CANADA CENTRE FOR MINERALS AND ENERGY TECHNOLOGY

by

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Work on the project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy Mines Resources Canada under the the Canada-Saskatchewan Mineral Development Agreement. Support was also received from the National Science and Engineering Research Council.

DSS File No. 55SS.24440-7-9187
DSS Contract Serial No. 23440-7-9187/01-SS
CANMET Project No. 140905
CANMET Scientific Authority: Dr. S. Vongpaisal

April 1998

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Chapter 1

by

F.F. Langford

1.1 Abstract

This research is in three independant projects. The first consists of chemical analyses of one location of the potash beds at PCS Mining, Cory Division. It shows that variation in the content of the halides is related to the stratigraphic position and probably related to depositional processes. The variation of sulphate, calcium, and strontium depend upon the amount of anhydrite or gypsum present. The second project concerns fluid inclusions in the halite. The lack of correlation of homogenization temperatures, and of isotopes of oxygen and hydrogen with stratigraphic position indicate that these minerals are not primary, and the isotopes further indicate that the parent fluids were probably derived from meteoric water. The third study assembled basic information on the Dawson Bay formation, which showed that the porosity and other aquifer properties were not well understood.

1.2 Executive Summary

The flooding in the potash mines in the Prairie Evaporite Formation of Saskatchewan, has sparked renewed interest in the geology of the Prairie Evaporite and the overlying the Dawson Bay Formation, Thus a close examination of the geology of this area is essential if we are eventually going to be able to pinpoint where these waters are coming from and how they can be stopped.

The project concentrates on the Saskatoon Potash Mining District, consisting of Townships 30 and 40 from Range 20 W2M to Range 14 W3M (24,000 sq. km.) more or less. The work reported here has the results of the examination of fluid inclusions which is completed at this stage. The examination of the chemical makeup of the potash beds has just started with an exploratory examination of one location at PCS Mining, Cory Division. The investigation of the diagenesis of the Dawson Bay Formation has completed the first phase.

The work reported here on the chemical composition of the potash beds is an attempt to complete the work of Chris Boys who is doing a study of the geology of the "Cory mine" (PCS Mining, Cory Division). It is hoped that there will be a significant aureole around anomalous areas in the potash beds to permit their detection. This type of study is somewhat of a long shot, but because geological detection has the potential of being so much cheaper than other methods it is worth pursuing. Therefore this investigation should be continued to establish if changes in composition occur near anomalous areas.

In the second study, the work on the fluid inclusions complements other work being done on isotopes of light elements. such as the investigation of the isotopic composition of formation water by M. Wittrup which has been useful in identifying sources of flood water. The work of Chipley presented here, shows that surface water seems to have been pervasive in most of the salt beds, even where anomalous features are not present. This raises many problems: because there is so little other evidence of this, it requires substantial re-thinking of our commonly accepted concepts.

The diagenetic history of the Dawson Bay Formation has not yet been done in detail by anyone. Very little is known of its overall porosity and permeability characteristics and the nature and origin of its pore-filling cements. The aims are to try to understand the paths of the fluid migration and examine in detail the mineralogy, both of the rock matrix and pore-filling cements.

Having done the background work, future progress will principally involve petrographic work, scanning electron microscope and microprobe analysis, cathodoluminescence, and such stable isotope work as is possible. Most of the samples will be collected from the Core Lab in Regina and any other samples that can be obtained from the potash companies will also be used. Work is being done on the competence of the Dawson Bay Formation rocks in the rock mechanics lab at the University of Saskatchewan under the direction of Dr. Doug Stead of the Department of Geological Sciences. We will try to correlate his data with the detailed geological information from this project.

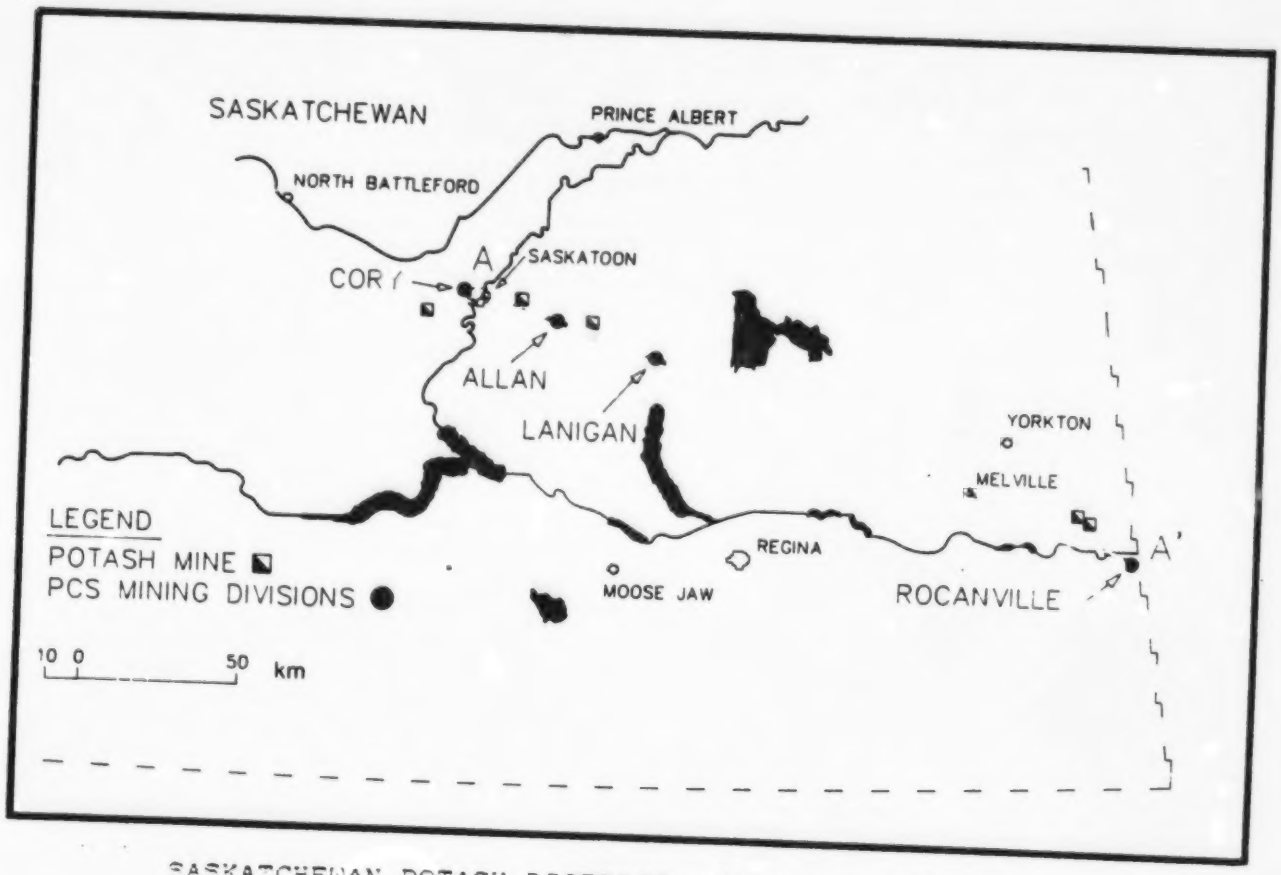
In the original proposal, a study of well records applying the methods of geostatistical analyses was proposed. We were unable to proceed with this because the well files are kept in IBM format and are incompatible with the VAX system used at the university. It seems that this problem if not solved has been surmounted, and it would therefore be possible proceed with this project.

1.3 Acknowledgments

This project was initially funded by the Saskatchewan Department of Energy and Mines, under the Canada/Saskatchewan Mineral Development Agreement. In 1987, this was taken over and funded through the Canada Centre for Mineral and Energy Technology, of Canada Energy Mines and Resources. In addition the materials and facilities for the study of the fluid inclusions were funded by grants to Dr. Kyser from the National Scientific and Engineering Research Council.

The project could not have proceeded without the encouragement and help of the Potash Corporation of Saskatchewan Mining Ltd; in particular the assistance of Dr. P. Mottahed and Mr T. Danyluk. The help, patience and good humour of the management and staff at PCS Mining, Cory Division is gratefully acknowleged. Mr Chris Boys comtributed data and advice. Members of the Saskatchewan Potash Producers Association provided

informed discussions and access to their mines.



SASKATCHEWAN POTASH DISTRICT (Wittrup, 1986)

Chapter 2

Feasibility of Using the Compositions of the Clay and Potash Beds to Indicate the Presence of Anomalous Areas.

by

F.F. Langford

2.1 Introduction

The purpose of this investigation was to use chemical analyses of the potash beds to determine what elements are present and and how they might be used to indicate the presence of an anomaly. The investigation was started by using specimens from the University of Saskatchewan section 103 at Cory Division of PCS Mining Ltd. (the mine is located about 5 km west of Saskatoon). This was a section that had been described and well sampled, and would provide a standard against which anomalous areas could be evaluated.

Unfortunately, for variously reasons, mostly involving changes in personnel, turn around time for analyses was in the order of 90 days. This meant that since the program started in November, the initial set of samples which were intended to act as a guide to the future work, were returned too late for the follow up. Thus this work did not reach the conclusions that were expected.

For the salts, analyses were done on the water-soluble portion. Analyses of the insolubles were only done on a few of the seams that contained more than 20% insolubles. Clay mineral analyses by XRD (done previously in another project) by C. Boys, indicated that the seams carried the same insoluble minerals that are found disseminated in the salts.

For section 103, the soluble fraction was analysed for the elements which would be expected in this environment: Na, K, and

Cl since these are the major components; Ca, Mg, and SO4, which are major components of seawater; and the halides, F, Br, and I. Analyses included Rb, and Sr because they commonly occur in association with K and Ca minerals respectively. Of the remaining elements P, Ba, Fe, Mn, Rb, Sr, were included because they were normally present in rocks of this type. As well the opportunity was taken to investigate the possible presence of Se, As, Co, Cr, Cs, Cu, Ni, V, and Zn, because of the possible economic overtones should they be present in significant quantity.

The principal method of evaluating the analyses was to examine them with respect to their stratigraphic level, because this permits one to make an evaluation of variations induced during sedimentary formation of the deposit. When this has been done, principally through the use of graphs relating the variation of the analysed component relative to stratigraphic position, then it is subsequently possible to investigate horizontal variations, which would be the ones that could possibly indicate the presence of anomalous areas. This stage of the investigation was not reached.

2.2 Section 103

A section in this study refers to an area in the Cory mine where the rocks have been described in detail, especially with reference to their stratigraphic position with in the mining section. Section 103 lies about 3000m west and 1200m south of the #2 shaft.

The normal mining zone lies between the No 3 seam of insolubles ("clay seam") and 300 cm below the No 1 seam. After mining, the upper part of the section is usually badly squeezed as the opening starts to close, and the upper seams, along which most of the movement occurs, become distorted. Therefore it is customary to use the No 1 seam as the reference for vertical measurements.

The geology of this section is shown in Figure 1.1. As in other parts of the mine, it is divided into units primarily on the basis of the seams of insoluble minerals (black bands in the diagram). The salts are named according to a scheme described previously by Langford et al. (1987). Their table 1 is reproduced here as table 1.1.

ROCK TYPE		A	B	C	D	F	G
DIAGNOSTIC FEATURES		Thick orange-red rims on many evenly distributed sylvite grains	Pale orange; low content of insolubles	Majority of small (0.5 to 5 mm) grains	Majority of thin red-rimmed sylvite grains	Abundant brown halite	Patchy reddish sylvite
TRANS-LUCENCE		Opaque	Low to high	Opaque to moderate	Opaque to low	Opaque to high	Low to medium, patchy
TEXTURE		Granoblastic, porphyroblastic	Granoblastic porphryoblastic	Granoblastic	Granoblastic	Granoblastic, porphyroblastic	Granoblastic
OCCURRENCE		Most common	Common	Minor	Common	Minor	Common
SYLVITE	Grain size	1 to 8 mm granoblastic, 1.5 to 12 mm porphyroblastic	0.5 to 8 mm granoblastic, 1 to 18 mm porphyroblastic	0.5 to 5 mm	1 to 12 mm, average 6 mm	0.1 to 5 mm	0.5 to 8 mm
	Grain shape	Subhedral, most anhedral	Anhedral	Anhedral, equant	Anhedral, equant	Anhedral	Anhedral
	Colour	Thick, orange-red to red fringes; clear to cloudy centres	Wispy orange; clear, cloudy	Orange to red	Red rims; clear to cloudy centres	Orange flecks	Orange-red to red
	Amount	High	Moderate to high	High	Moderate	Low	Moderate to low
	Other	Fractures; insolubles as inclusions	Halite inclusions	Poikiloblastic (?)			Remnant grains
HALITE	Grain size	1 to 9 mm granoblastic; 2 to 15 mm porphyroblastic	1 to 9 mm granoblastic; 1 to 18 mm porphyroblastic	0.5 to 5 mm	1.5 to 12 mm, most 4 to 10 mm	0.5 to 12 mm,	1 to 12 mm, maximum 20 mm
	Grain shape	Anhedral to subhedral	Anhedral to subhedral	Anhedral	Anhedral to subhedral	Most anhedral	Most anhedral
	Colour	Clear to cloudy	Clear to cloudy	Clear to cloudy	Most clear	Brown tint	Clear to cloudy
	Amount	Low to moderate	Moderate to low	Low	Moderate	High	Moderate to high
	Other	Thin films; inclusions				Insolubles as inclusions	Thin films
INSOLUBLES	Amount	Variable	Less than 2 per cent	Low	Moderate	Moderate to high	Low to moderate
	Colour	Mostly green-grey	Green-grey	Green-grey	Green-grey; some brown	Green-grey, brown or both	Mostly green-grey
	Distribution	Mostly interstitial; inclusions; especially with halite	Inclusions and interstitial; especially with halite	Most form porphyroblasts	Seamlets, inclusions and interstitial.	Variable	Inclusions are numerous; interstitial

Table 1.1 Summary of the characteristics of the rock types used in this study. Taken from Langford et al. 1987, table 1.

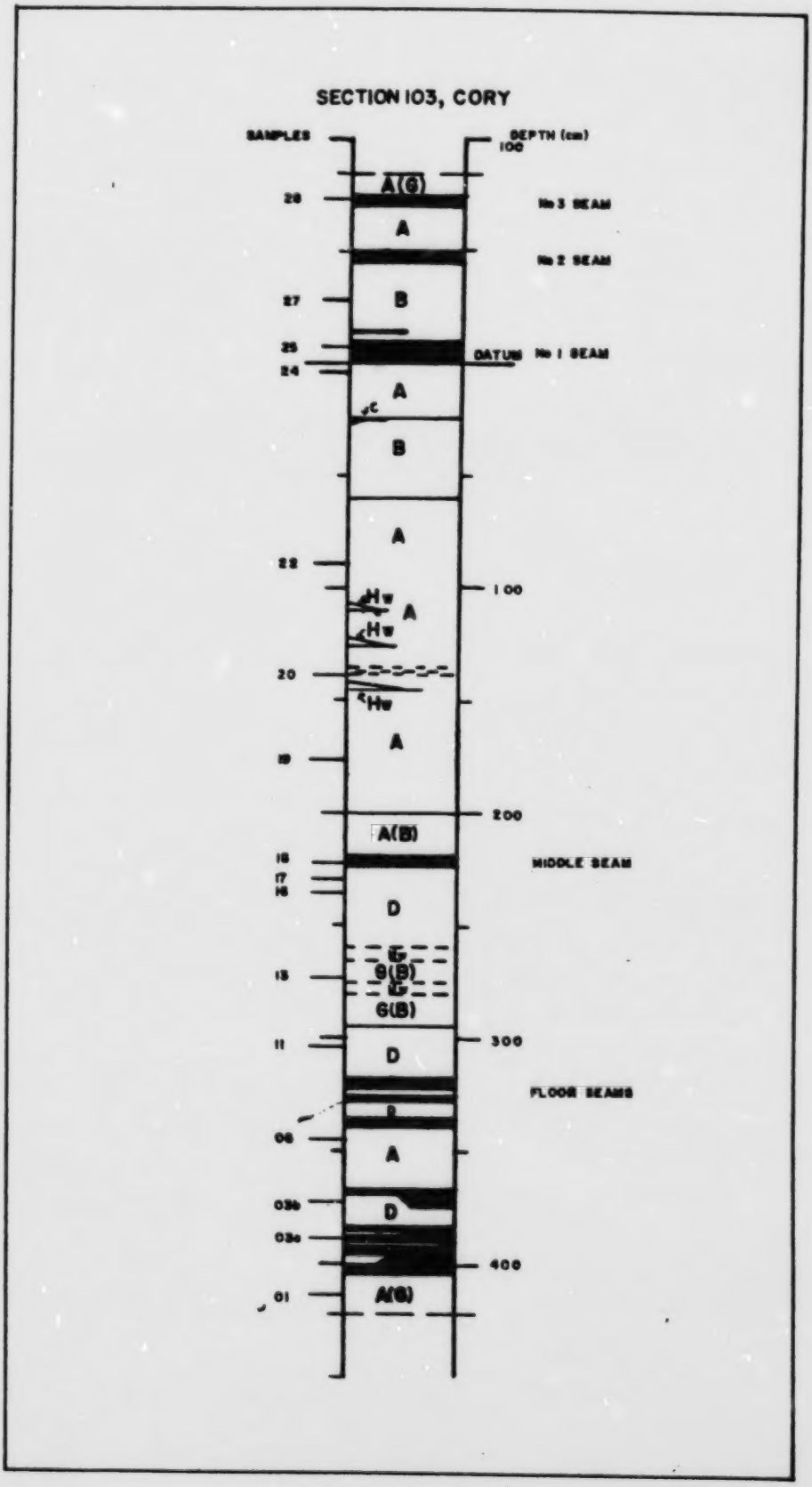


Figure 1.1 Stratigraphic column of section 103 at the Cory Division, PCS Mining. See text for explanation.

The "A" and "D"-types indicate the main ore type of red sylvinite. The D-type differs from the A-type in having the red colouration more confined to the rims of the sylvite grains, rather than homogeneously distributed in the sylvite grains as in the A-type. The "B"-type is characterized by pale orange sylvite grains which produce a pale, transluscent rock. Halite units are indicated by "H" with a letter to indicate colour (W = white). The "G" indicates a rock largely composed of halite with 10 to 50% scattered grains or patches of pink or red sylvite. Any secondary attributes are indicated in terms of rock-types and placed in brackets.

2.3 Analyses of the Salts

The analyses of the water-soluble component of samples consisting of more than 90% halite and sylvite are given in table 2. The sample numbers refer to those indicated in figure 1.1, and the depths refer to distances in cm from the #1 seam (up is negative). The samples are described in Appendix 1.

2.3.1 Sodium, Potassium, and Chlorine

These elements are the principal components of the potash ore and account for most of the sample. Figure 1.2 is a graph of the compositions of the rocks plotted against their stratigraphic level in cm. To correlate with figure 1.1, the #1 seam (at 0), the middle seam and the upper floor seam have been indicated.

In the graph it is noted that the Cl content is a reflection of the K curve which is to be expected, since the proportion of Cl in halite is higher than in sylvite. The amount of K and Na remain fairly constant except for an excursion between 200 and 300 cm below the #1 seam. This is to be expected because the section in figure 1.1 indicates the presence of halite bands separated by G-type rock. Except for samples 16 and 13 at depths of 240 cm and 280 cm respectively the amounts of K and Na are fairly consistent. It should be noted that the extra halite in samples 16 and 13 coincides with variations of some of the trace constituents.

MAJOR CONSTITUENTS %										
SP. NO	103.1	103.6	103.11	103.13	103.16	103.17	103.19	103.22	103.24	103.27
DEPTH	415	345	305	280	240	230	125	88	5	-25
ELEMENTS										
Cl	52.8	54.4	55	58.7	56.2	53.2	52.2	51.3	52.4	54.2
K	19.8	21	17.2	8.22	13.6	19.2	24.8	22.8	23	25.3
Na	22.2	21.8	24	32	27.3	22.1	18.2	19.1	18.8	18.9
SO4 ppm	4770	6090	16200	3900	6630	4770	4500	15000	2620	1290
TRACE CONSTITUENTS ppm										
B	ND	.6	.7	.5	.5	.6	.6	1.4	.8	1.2
Br	525	542	542	545	575	530	563	520	520	578
F	2.8	9.8	11	.04	8.4	12	12	13	22	2.1
I	.08	.1	.08	.44	.1	.07	0	.04	.06	.02
P	4.6	6.1	6.3	6.1	2.1	4.3	4.9	4.2	7.2	5.2
Se	.01	.01	.01	0	.01	.01	0	.01	.02	0
As	0	0	0	0	0	0	0	0	0	0
Ba	.8	.3	.08	0	.06	.1	.06	.18	.25	.19
Ca	1660	2370	5980	1600	3160	2240	2120	4970	1100	528
Co	0	0	0	.07	0	.08	0	.05	.09	.06
Cr	.1	.15	.16	.16	.14	.25	.25	.26	.21	.2
Cs	0	0	0	0	0	0	0	0	0	0
Cu	.29	.27	.08	.18	.09	.07	.07	.12	.07	0
Fe	.63	.93	1.1	.89	1.3	1.2	1.2	1.7	1.6	.96
Mg	74	58	91	104	96	122	122	157	159	75
Mn	.4	.25	.22	.22	0	.13	.13	.18	0	.22
Ni	0	0	0	0	0	0	0	0	.06	0
Pb	0	.2	0	.4	0	0	0	.6	.4	.6
Rb	58	21	34	17	25	60	60	66	41	63
Sr	11	17	38	13	21	17	17	40	9.4	3.3
V	0	0	.6	.6	.6	.8	.8	1	.8	.8
Zn	.88	.47	0	.08	0	.61	0	0	0	0

Table 1.2 Chemical analyses of the soluble component of the potash mining unit at section 103. Analyses done by the Saskatchewan Research Council, on samples provided by F.F. Langford.

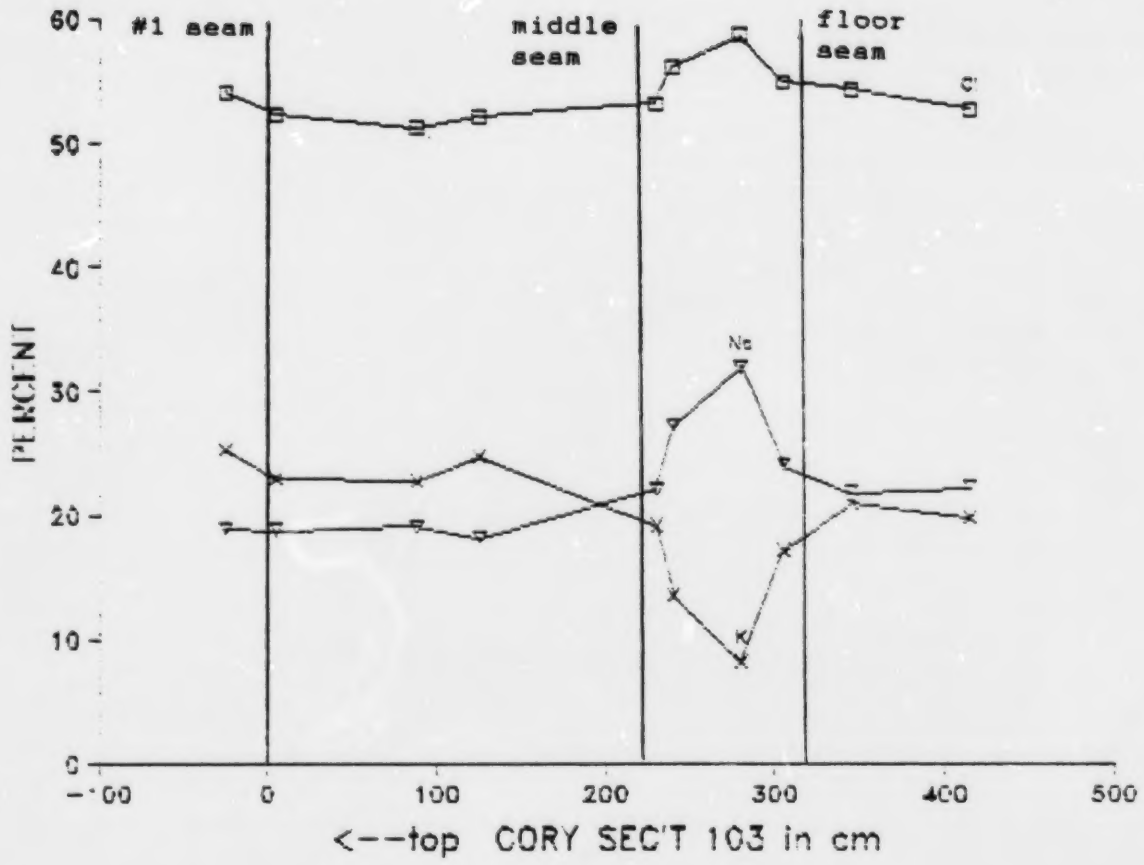


Figure 1.2 Graph to show variation of K (x), Na (▼) and Cl (o) with depth relative to datum (see fig. 1.1, and table 1.2.).

2.3.2 Bromine and Chlorine

Bromine is commonly used as an indicator of the nature of the fluids from which the salts crystallized. The graph (figure 13) indicates a rather erratic distribution which is not easily explained. It should be noted that these analyses are done on whole rock samples and are not directly comparable to most other analyses in the literature which are done on individual minerals.

Fuzesy (1982) gives analyses that indicate that the halite in the Esterhazy member of the Prairie Evaporite Formation in the Rocanville area has about 125 ppm Br, and the sylvite about 1300 ppm. Wardlaw (1968), indicates that Br is between 100 and 200 ppm in halite and between 1000 and 2000 ppm in sylvite in a core located at 1-13-32-20W2. Since at Cory, the sylvinite rock contains about equal parts halite and sylvite, similar quantities could explain the values in the order of the 500 to 600 ppm that were found in these analyses.

In general, the Br curve follows the K curve as would be expected if the sylvite contained most of the Br in the rock. However there is an upward excursion at sample 16 (240 cm) which correlates with a decrease in K. In the next sample, 13, which has the least K, the Br content returns to 545 ppm which is about average. More data is clearly needed; particularly analyses of the individual sylvite and halite grains.

2.3.3 Fluorine, Bromine, and Iodine

The behaviour of bromine has been considered above, and as the graph in figure 14 shows it has little relation to either fluorine or iodine. As is typical in evaporites, iodine is very low. The highest value occurs in sample 13 (280 cm). This is the sample that is richest in halite, however the adjacent samples are relatively low in halite but have normal values for iodine.

The fluorine seems to have an erratic behaviour. It drops to a low value in sample 13 like the iodine, but it also drops to equally low values in sample 27 which is the richest of all in potassium. It is possible to see some apparent cycles in its behaviour. Going upward from the bottom, the amount of fluorine increases until the level of the halite-rich zone at sample 11 (305) above which it decreases markedly. From there to the base

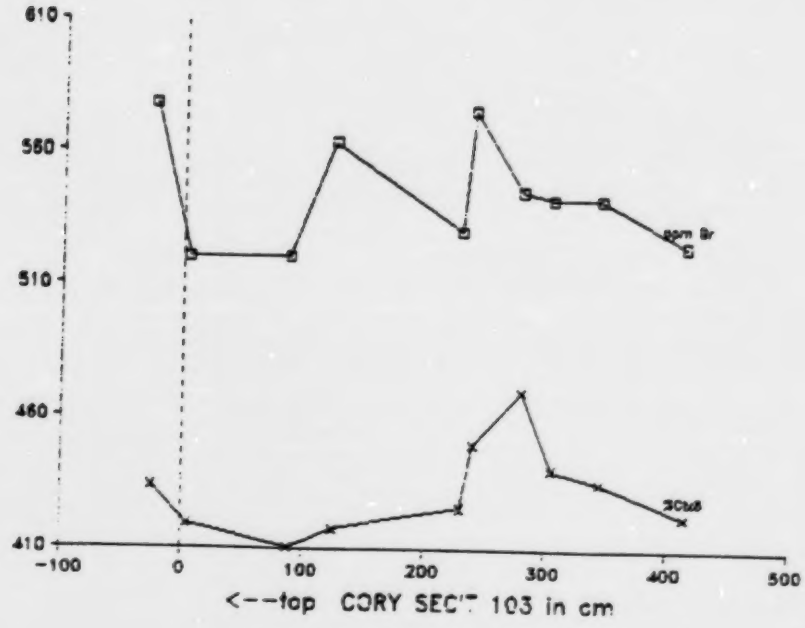


Figure 1.3 Graph to show variation of %Cl(x) and ppm Br (o) with depth relative to datum (see fig. 1.1). Note the Cl is indicated as 8X its value in table 1.2.

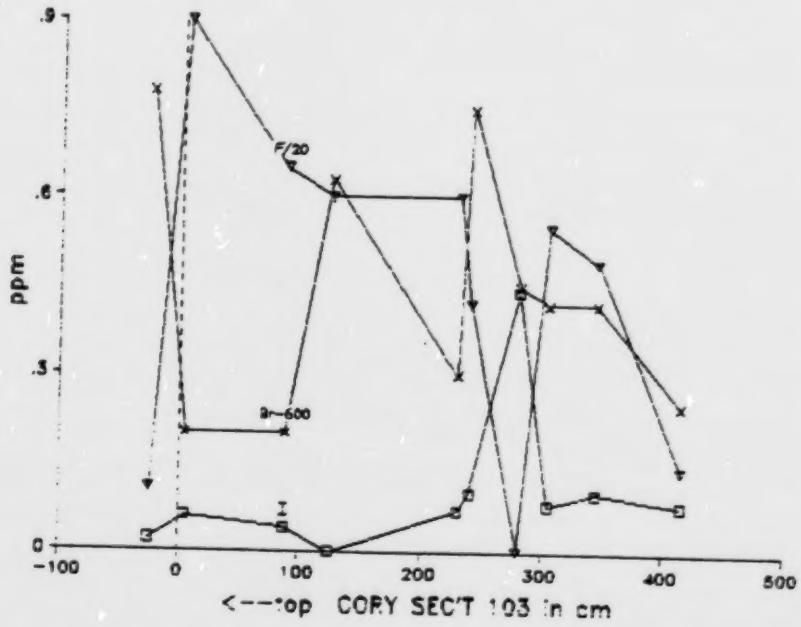


Figure 1.4 Graph to show variation of ppm I (o), Br (x), and F (v) with depth relative to datum (see fig. 1.1). Note the Br is indicated as [Br-600]-0.1], and the F is indicated as F/20 of the values in table 1.2.

of the middle seam it increases once more. Above the middle seam the value holds, only to increase below the #1 seam. The uppermost sample shows another major decrease. This type of behaviour may indicate different sedimentation units.

2.3.4 Sulphate, calcium, and strontium

The very tight correlation of these elements that is clearly evident in the graph of figure 5 is undoubtedly due to the presence of some gypsum or anhydrite that is soluble in water: possibly in fluid inclusions. The amount of sulphate exceeds the amount of calcium required to make anhydrite or gypsum by about 10%. This is probably accounted for in part by the strontium. If these elements occur in residual fluids, they are probably in saturated solutions and normal stoichiometry is not expected.

The anhydrite is abundant in two samples. The sample at 325 cm depth is just above the floor seams, which would go well with a theory that called for formation of the insoluble seam as the residual of erosion, and the anhydrite could represent the commencement of new deposition. This is invalidated somewhat by the occurrence of an equal enrichment in the middle of the most homogeneous part of the main mining sequence, without associated clay.

2.3.5 Rubidium, and Potassium

Rhubidium is expected to substitute for potassium in the sylvite, but it can be seen from the graph of figure 6, that the amount of Rb in the potash ore varies independantly of the amount of sylvite. The amount of Rb present is similar to that found by Wardlaw (1968) which was mostly between 50 and 120 ppm in sylvite. The major change in abundance generally coincides with the halite influx, but is more extreme than explained simply by the change in mineralogy, and probably reflects a difference in sedimentary environment. The variation seems to bear no relation to the presence of seams of insolubles.

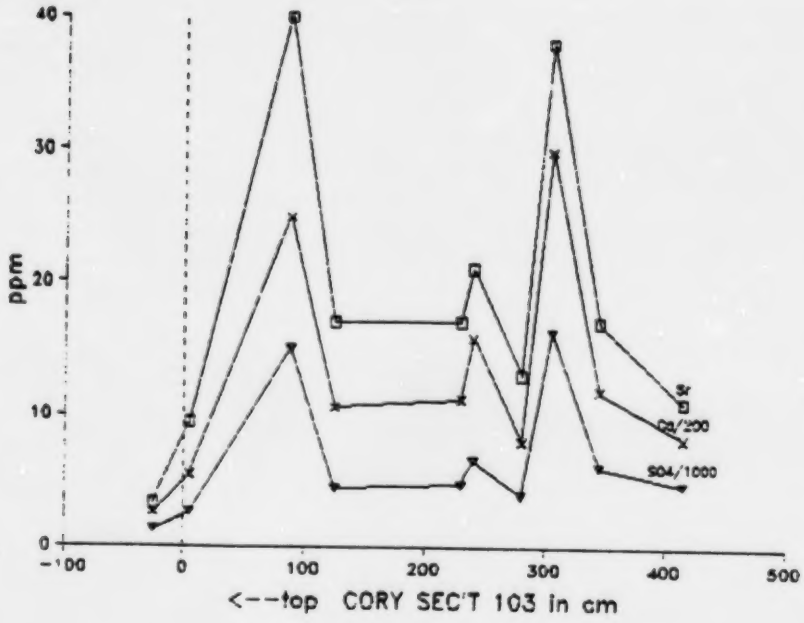


Figure 1.5 Graph to show variation of ppm of Sr (□), Ca (x), and SO4, with depth relative to datum (see fig. 1.1). Note the Ca is indicated as Ca/20, and the SO_4 is indicated as SO_4/1000 of the values in table 1.2.

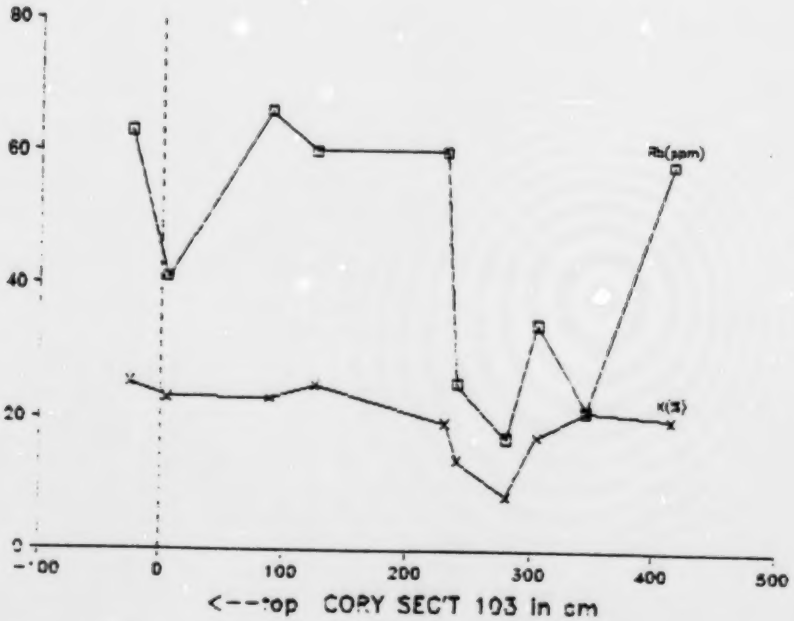


Figure 1.6 Graph to show variation of ppm of Rb (□), and %K (x), with depth relative to datum (see fig. 1.1), of the values in table 1.2.

2.3.6 Iron and Manganese

The red colour of the potash beds is due to the presence of iron, mostly in the form of hematite. The soluble iron measured here, shows in the graph in figure 7, an interesing if not explained, gradual increase through the section. Manganese which is a common component of sediments is low, but shows an inverse relationship to iron, except for the deflection at sample 16 (240 cm), which is not as halite-rich as sample 13 at 280 cm.

2.3.7 Chromium, Copper, and Zinc

Heavy metals are not abundant in these rocks, and of those looked for, these three are the most persistent. As seen in the graph of figure 8, the zinc has a rather erratic behaviour. The chromium and copper seem to indicate when taken together distinct sedimentation units separated by seams of insolubles. However the abundance is less than 1 ppm, so that these are not as abundant as the other elements

2.4 Analyses of the Insolubles

Eleven samples from the insoluble seams were analysed and the results are presented in table 3. The results are for the common rock-forming elements expressed as oxides. The samples are located in figure 1, and brief descriptions are given in appendix 2.

According to C. Boys (personal communication) in order of abundance the insolubles consist of dolomite, clays, quartz, with lesser anhydrite, hematite, and goethite. Dolomite makes up 40 to 45%, of the insolubles, being a little higher in the seams than in the insolubles disseminated in the salts. The clay minerals in order of abundance are illite, chlorite, septechlorite, and swelling chlorite. Smectite is present but composes less than 1% of the clay component. The mineralogical composition does not vary widely with stratigraphic position.

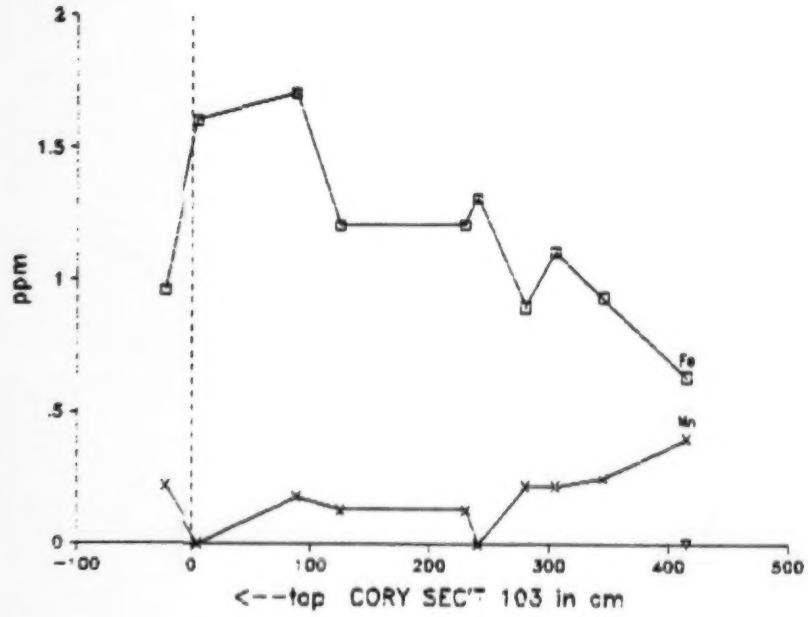


Figure 1.7 Graph to show variation of ppm of Fe (□), and Mn (x), with depth relative to datum (see fig. 1.1), of the values in table 1.2.

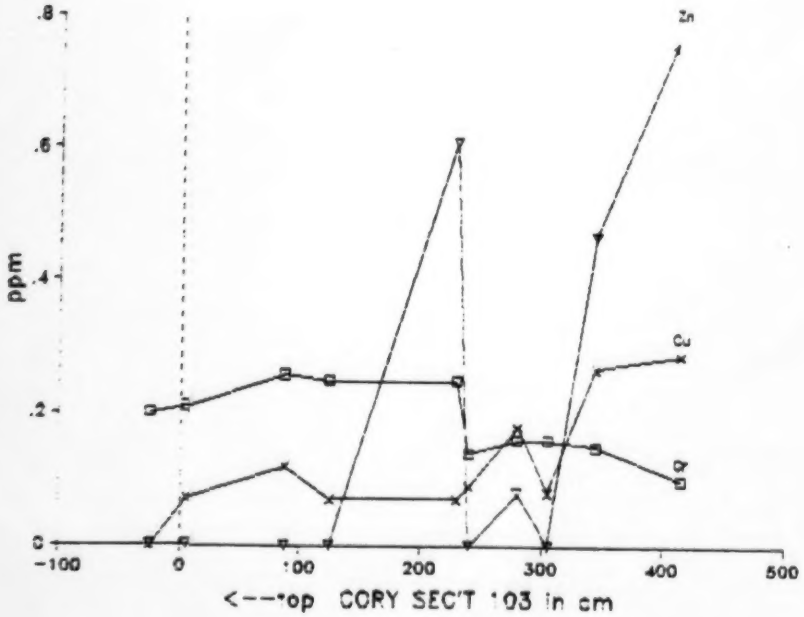


Figure 1.8 Graph to show variation of ppm of Cr (□), Cu (x), and Zn (▽) with depth relative to datum (see fig. 1.1), of the values in table 1.2.

SECTION 103 CORY, CLAY XRF /88

SAMPLE NO	103.3A	103.3A1	103.3A2	103,3B	10C	103,18
DEPTH *	490	490	490	475		322
OXIDES	11	10	9	8	7	6
SiO2	45.9	45.36	45.89	44.97	32.68	43.75
TiO2	.571	.561	.572	.55	.164	.52
Al2O3	11.01	10.64	11.1	10.36	4.9	9.63
Fe2O3	4.43	4.44	4.39	3.71	1.82	3.52
Mn	.04	.04	.04	.04	.02	.04
MgO	14.48	14.13	14.54	14.64	11.78	16.82
CaO	13.1	13.39	13.03	14.53	7.81	15.07
Na2O	.086	.195	.196	0	26.788	.416
K2O	4.15	4.09	4.15	3.94	1.19	3.36
P2O5	.25	.26	.25	.28	.17	.27
TOTAL	105.027	103.106	103.168	101.02	94.322	99.396

* DEPTH REFERS TO #1 SEAM AS 1m

SAMPLE NO	103,20	103,28A	103,28B	103,25	CCP-RB
DEPTH *	248	25	25	95	
OXIDES	5	4	3	2	1
SiO2	46.77	40.53	40.81	44.77	40.25
TiO2	.586	.415	.378	.574	.391
Al2O3	10.877	8.58	8.78	9.67	7.74
Fe2O3	3.79	4.04	3.41	3.49	3.48
Mn	.04	.04	.04	.04	.04
MgO	13.7	17.82	18.83	15.92	15.14
CaO	13.48	17.9	16.68	15.25	22.26
Na2O	.214	0	.149	.137	.028
K2O	4.19	2.83	2.77	3.35	2.94
P2O5	.27	.28	.26	.29	.33
TOTAL	98.917	96.435	95.107	95.491	93.599

Table 1.3 Chemical analyses of the insoluble seams of the potash mining zone at section 103. Analyses done by XRF at U of S. Sample CCP-RB is from Central Canada Potash mine. Depths are recorded with #1 seam as datum given as 1 m, increasing downwards. Values are in weight percent.

The chemical analyses reported here were a set that was selected with a view to testing the measurement and preparation process; hence the repitition of samples. Sample 10C is from the "10 foot seam" which is in the halite 3 m above the #3 seam. The high sodium value indicates that the halite was not leached from the sample before analysis. Sample "CCP-RB" is from the Second Red Beds of the Dawson Bay Formation, at Central Canada Potash mine.

The analyses are basically similar, but there are some differences that might allow differentation of one seam from another. This could be of great use in interpreting collapse structures. If it is possible to identify the clay fragments in these collapse areas and relate them to the stratigraphic bed they come from, it is possible to determine the minimum height of the collapse.

The analyses do not add up to 100%, chiefly because carbonate which, in the form of dolomite, makes up a considerable proportion of the samples was not accounted for. Some of the constituents, such as TiO2 and P2O5, differ very little from sample to sample, and thus do not serve to differentiate seams. The K2O and Na2O tend to be suspect as constituents of the insolubles, since they are major components of the salts, but the leaching, except for sample 10C, seems to be good.

The MgO and CaO are mainly determined by the amount of dolomite present. The ratio between them is not consistent however, and some of the MgO probably relates to the amount of chlorite present. If this is true then this ratio might be useful in distinguishing seams. It appears that the CCP-RB sample is rich in CaO. The amount of SiO2 and Al2O3 is probably governed by the amount of clay present. Inspection of table 3, seems to indicate an inverse relationship with the MgO and CaO which would bear this out. Some free quartz is present and this could explain why the ratios are not consistent, and could be exploited to characterize seams.

2.5 Conclusions

The in the salts, the variation of the elements appears to be generally related to the original stratigraphic variation of the major components of the rock. Accordingly variation in abundance is most affected by changes in the sylvite to halite ratio. At the level of information obtained here it is not

possible to establish the effect of anomalous ground, but unless the solutions that produced such areas were particularly penetrating, it is unlikely that they extended far in advance of the alteration front.

In the insoluble seams, we do not yet have enough samples analysed to give definitive results on the use of these for correlation. The possibility that changes in the composition of the seams may indicate anomalous ground has not been touched. Additional analyses are needed, and are underway but have not yet been received.

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2.7 APPENDIX 1

Descriptions of Samples of Soluble Salts from Section 103 from Cory Divsion, PCS Mining Ltd.
(See table1-2)

103-1

From the base of the section, light A-type sylvinite that has paler and more uniform orange grains than usual tending to resemble B-type sylvinite. Some greenish grey clay is disseminated throughout. Towards the base it tends to be darker and more typical A-type sylvinite, consisting of 5mm grains.

103-6

Taken 345 cm below #1 seam, this sample is typical (5 mm) D-type sylvinite. It is close enough to a clay seam that it shows some of the darker colour typical of sub-clay units.

103-11

Taken 305 cm below #1 seam. The unit grades from light A- to B-type sylvinite, although mapped as D-type sylvinite. The sample was taken from D- to A-type sylvinite.

103-16

Taken 235 cm below #1 seam. The A-D-type sylvinite was typical and had grains up to 5mm across. The unit contains a layer of B-type sylvinite that was not included.

103-17

Taken 230 cm below #1 seam. Sub-clay unit taken close to the base of the clay. It is D-type sylvinite with grains up to 75 mm.

103-19

Taken 125 cm below #1 seam. Strong orange A-type sylvinite, taken from a homogenous unit, that has about 5% insolubles. Halite tends to be in 1 to 2 cm clots.

103-22

Taken 88 cm below #1 seam. The orange A-type sylvinite came from a homogenous unit with about 5% insolubles. The halite grains are about 10 mm in size and the orange sylvite forms a matrix.

103-24

Taken 5 cm below #1 seam. This subclay D-type sylvinite is coarse grained (up to 1 cm). The sylvite occurs as discrete rimmed grains. About 5% insolubles are present. Sample is a little small for grain size.

103-27

Taken 25 cm above #1 seam. The B-type sylvinite is pale orange, massive, and coarse grained (5mm), and located between #1 and #2 clay seams.

2.8 APPENDIX 2

Descriptions of Samples of Insolubles from Section 103
from Cory Divsion, PCS Mining Ltd.
(See table 3)

103-2

This lowest seam is underlain by 5 cm of brown halite which differs from the underlying C-type in having about 10% interstitial brown halite which causes the overall brown colour. The halite is colourless and clear, and grains are 4 to 10 mm in size. The clay ranges from hairline seams to insertitial clots up to 3 mm.

The seam is 6 cm thick, and consists of 70% clear halite in grains 3 to 5 mm in size separated by 1 mm thick films of brown clay. Margind of the halite grains are irregular and pitted giving the appearance of corrosion. In the bottom 1 cm there is a tendency for apparent flattening of the grains to show a foliation parallel to the bedding. Above that is a 1 cm zone of slightly coarser halite with a little less clay.

The base of the seam is planar in hand specimen, and marked by a film of browm clay, through which a few halite grains project from above or below. Some of the grains below the basal film appear to be truncated to give the planar surface. The top of the seam is marked by the abrupt appearance of coarse grained sylvinite with no more than 2% grey interstitial clay. The upper surface of the seam has a relief of about 1cm on a hand specimen scale. It marks the change from clay and halite to sylvanite sedimentation.

103-3a

Taken 390 cm below #1 seam.(there is some ambiguity exactly where the specimen is: it is difficult to correlate it with the photos)

A two-seam unit, lower is 3.5cm thick and mostly massive.

Separated from upper by 3.5cm of redskin potash. Upper 1.5cm about 20% interstitial green clay, 70% halite and 20% sylvite.

The lower seam consists of a basal medium brown massive clay with about 15% flattened clear colourless halite grains in the order of 1X3mm. This part of the seam is 1.5cm thick and overlain by 1.5cm of massive clay without included halite except for a few vertical veins if fibrous orange sylvanite [?]. The clay is mottled, greenish grey in the lower part and pale brown in the upper part. Over most of the specimen, the greenish part seems to be a layer that is slightly irregular in its contact with the underlying clay, but on one place it is broken so that a 1cm block is partially tipped into the underlying clay. The top of this lower seam consists of 0.5cm of brown clay with included 1X3mm colourless halite grains. The grains give a foliation and increase to about 60% at the top. The clay seam passes abruptly into coarse grained red-rimmed potash ore.

The upper seam consists of a change from the coarse-grained red-rimmed potasn ore to a layer of 70% clear colourless halite in 3mm grains, which are separated by films and insertial clots of greenish grey clay. The clay constitutes only about 15% of the rock. Above the seam the rock reverts to red-rimmed potash ore.

103-3b

This seam which is about 6.5cm thick, is composed of greenish grey clay with about 20% colourless clear rounded grains of halite averaging 5mm in size. The lower contact is a pronounced erosional surface. It is separated from the underlying coarse-grained red-rimmed potash by an irregular 1 to 2cm layer that contains about 50% patches [up to 1cm] of 1 to 2mm grains of orange sylvanite and halite. This in turn is inderlain by an 8mm layer of the potash ore that has 15% clay in intergranular films.

The basal surface of the clay seam is a sharp undulating surface with 1cm relef. Above this the clay seam is uniformas described above. Small red grains [1 to 2mm] are scattered throughout and are sylvite. They tend to have an insertial shape, and fill a few tiny fractures. The upper surface grades into the potash ore over a distance of 0.5cm.

103-18

Taken 222 cm below #1 seam. This is a 5 cm zone with about 25% insolubles in discontinuous laminae and interstitial clots up to 1 cm elongate parallel to the bedding. The bulk of the rock is composed of pale brown halite in 2 to 5 mm grains. The surrounding rock is D-type sylvinite in grains up to 1 cm.

103-20

This is a zone of sylvinite enriched in insolubles. They consist of greenish grey clay in interstitial clots up to 8mm in equally coarse grained salts. The sylvinite is typical A type with some development of red rims in potash grains.

103-25

Sample of the #1 seam is mainly massive greenish grey insolubles containing about 25% pale brown halite in grains 1x2mm in size. A few scattered grains of halite are up to 1 cm. The contact with the A-type sylvinite is sharp but there are some satelite disseminated layers abiut 1 cm thick.

103-28

Sample of the #3 seam is massive greenish-grey insolubles containing about 35% salt in grains up to 5 mm. The rock is quite sheared.

Chapter 3

Fuid Inclusion Evidencefor the Deposition and Diagenesis of the Patience Lake Member

by

D.B.L. Chipley & T.K. Kyser

3.1 ABSTRACT

Low bromine concentrations, radiometric ages, textural relations and large scale dissolution and collapse features in Devonian potash deposits of the Elk Point Basin in southern Saskatchewan indicate that diagenetic processes and late influxes of water have variably recrystallized the salts. Lack of correlation between homogenization temperature (T_h), del D or del ^{18}O values of fluid inclusions in the salt with stratigraphic position further indicates that the sequence is not primary. The stable isotopic compositions of fluid inclusion waters, including those in chevron-texture halites, are not those expected for primary crystallization waters and in conjunction with T_h indicate recrystallization occurred at temperatures of 35°C to 70°C from water originating in formations above the Prairie Evaporite Formation. Using T_h as an estimate of the depth of burial and stable isotopes as indicators of the source of fluids, three major recrystallization events related to the evolution of the Elk Point Basin can be realized.

3.2 Introduction

During Middle Devonian time, the Elk Point Basin covered most of Alberta, the southern half of Saskatchewan, southwest Manitoba and extended into the U.S.A. (fig. 2.1). The basin was bounded to the north and west by a series of ridges and arches but due to erosion the true eastern extent is unknown. The Pacific coast was near the present Alberta - British Columbia border and the Elk Point Basin was centered at approximately 10oS latitude. Restriction of the basin by the Presqu'ile Barrier Reef resulted in the deposition of a sequence of evaporites including the Prairie Evaporite Formation (fig. 2.2).

The Prairie Evaporite Formation lies conformably on the irregular topography of reefs and reef-like mounds of the Winnipegosis formation (fig. 2.2). Above the Prairie Evaporite Formation, there is a series of Devonian cyclic deposits of limestone, dolomite and evaporite minerals which comprise the Dawson Bay, Souris River, Duperow and Nisku Formations. Lying unconformably on these Devonian deposits are the Lower Cretaceous sands of the Manville Group which are further overlain by younger Cretaceous shales. The section is topped by Pleistocene glacial deposits and Recent sediments.

The Prairie Evaporite Formation is continuous over a large portion of southern Saskatchewan except where the salt has been removed as a result of solutioning (fig. 2.1). In Saskatchewan, the formation is more than 400 m thick in some places and is buried to depths of as much as 2750 m (Fuzesy, 1982). Four potash-rich members, the Patience Lake, Esterhazy, Belle Plain, and White Bear, all occur near the top of the Prairie Evaporite Formation (Fuzesy, 1982). The Patience Lake member, which is the member extracted at the Cory mine, consists of sylvite and halite (fig. 2.2). The top of the ore zone at the Cory mine is defined by three laterally continuous clay seams called the #1, #2, and #3 clays (fig. 2.2) (for general geology see Fuzesy, 1982, and Holter, 1969).

Recrystallization of the evaporite minerals has been suggested from the results of various studies. Lower than expected bromine concentrations in halite (Wardlaw,1968), intergrowth and overgrowth textures among halite, sylvite and carnallite (McIntosh and Wardlaw, 1968), large scale dissolution

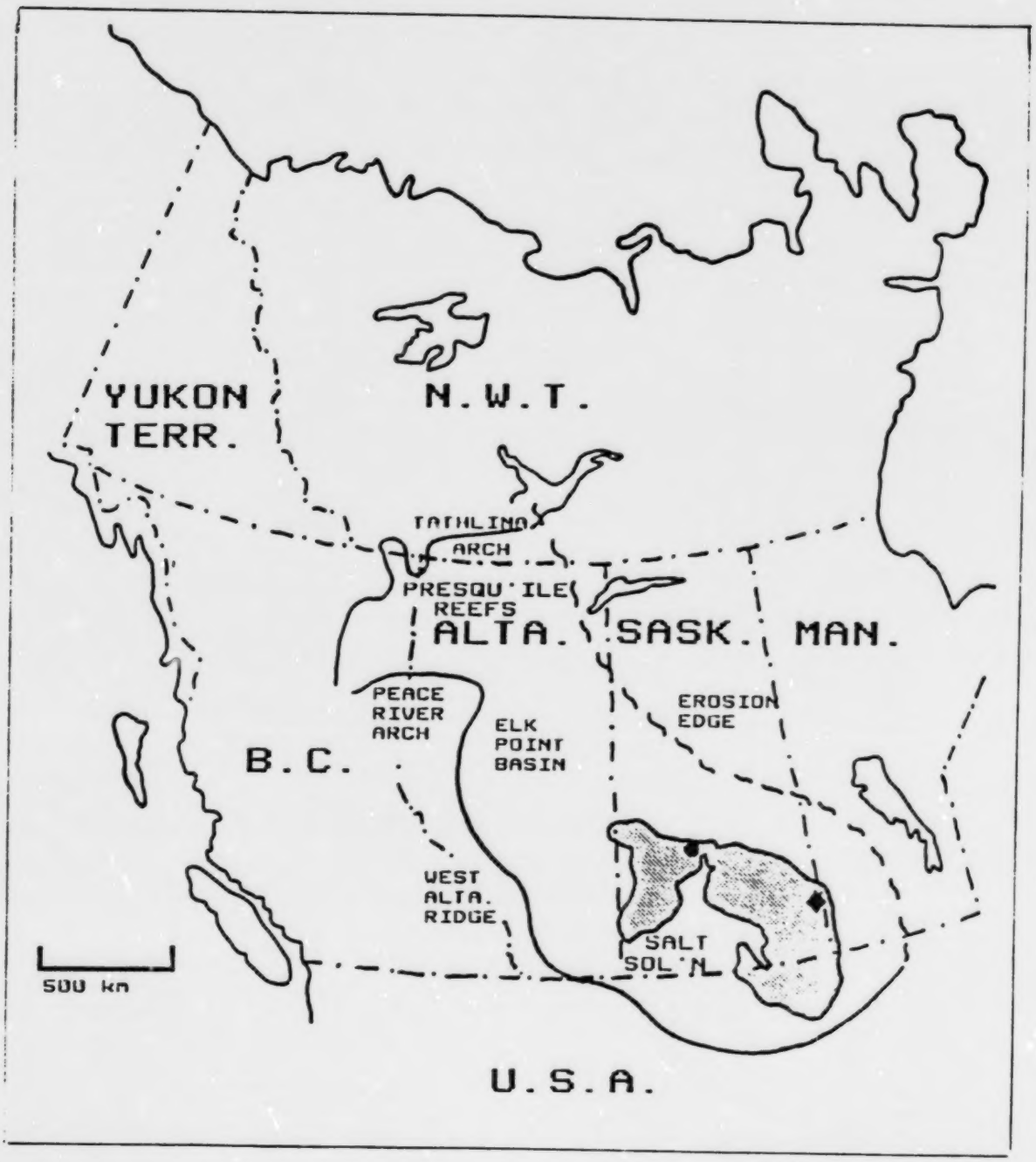

Figure 2.1 Location map outlining the Elk Point Basin, the extent of the potash (stripped area) and the location of mines●PCS Cory,◆PCS Rocanville (modified from Burrows and Krause, 1987 and Fuzesy, 1982).

and collapse features (Gendzwill, 1978; Simpson, 1978), and radiometric ages (Baadsgaard, 1986) all indicate that recrystallization of the Patience Lake Member and possibly other members has occurred. The recrystallization appears to have occurred mainly during Cretaceous time (Baadsgaard, 1986) when the basin was at its maximum depth of burial, although the range in possible ages is substantial suggesting that there may have been several recrystallization events.

Because crystallization or recrystallization normally involves aqueous fluids, the salt may trap these solutions as fluid inclusions during crystal growth. The solutions trapped within these fluid inclusions could be connate water from the original deposition of the salt or may represent subsurface fluids that interacted with the salt at a later time. The initial brine involved in deposition of the evaporite sequence is most likely trapped within the fluid inclusions of the chevron-texture halites which are thought to grow at the sediment-water interface (Wardlaw and Schwerdtner, 1966). Transparent grains of halite found associated with or replacing the chevron halites are younger and secondary (Wardlaw and Schwerdtner, 1966), and therefore should trap recrystallization fluids.

The temperature at which fluid inclusions are trapped should reflect either the temperature at which the host crystal formed originally, if the inclusions are primary or the approximate depth at which recrystallization of the halite occurred, if the inclusions are secondary. Similarly, the hydrogen and oxygen isotopic composition of the water from these inclusions can be used to characterize the original water of deposition if trapped in primary inclusions or later solutions contained in secondary inclusions (Knauth and Beeunas, 1986).

In this study, the trapping temperatures and isotopic composition of hydrogen and oxygen of waters contained within fluid inclusions in halite from the PCS Cory mine are used to determine the source of fluids related to the formation and recrystallization of a portion of the Prairie Evaporite sequence. This is achieved by comparing the stable isotopic composition of the included waters to those of the formations above the Prairie Evaporite (Wittrup et al, 1987), and using the trapping temperatures of the fluid inclusions to estimate the depth of burial at the time of formation of the halite.

3.3 Experimental

Samples of potash were collected from the mining face of the PCS mine at Cory and cut 0.5 cm to 1.0 cm thick for petrographic description. Selected crystals were removed from the slab and the size, concentration, texture and composition of the fluid inclusions noted. The inclusions were cooled to form a salt cube (daughter) if one was not already present and then heated to obtain a minimum temperature of trapping from the temperature at which the daughter crystal dissolved.

Selected samples containing well-characterized inclusions were cleaved to give one temperature generation of inclusions. These samples were carefully cleaned of foreign minerals (carbonates, sulfates and sylvite) and melted in vacuum with an induction furnace to release the fluid from the inclusions. The resulting gases consisted predominantly of water with minor CO_2 and SO_2 which were collected in a trap at -196 ^{o}C and separated by differential freezing. The release of CO_2 and SO_2 suggests that either solid carbonate and sulfate phases existed within the sample, or carbonate and sulfate ions were contained within the water of the fluid inclusions. The hydrogen and oxygen isotopic composition of the waters were then analyzed using the method of Kishima and Sakai (1980) for small water samples. All values are reported in the familiar "del" notation in units of per mil relative to SMOW (table 1). Duplicate analyses and analysis of standard waters using the same technique indicate a reproducability of 5 per mil in oxygen and 8 per mil in hydrogen.

3.4 Results

All the fluid inclusions in the halite were in the shape of cubic negative crystals. The fluid inclusions were of three types: (a) single phase brine filled inclusions, (b) two phase, brine and salt daughter inclusions and (c) two phase, brine, salt daughter and sulfate or carbonate daughter inclusions (fig. 2.3 a,b,c). Single phase inclusions range in size from 3 to 12

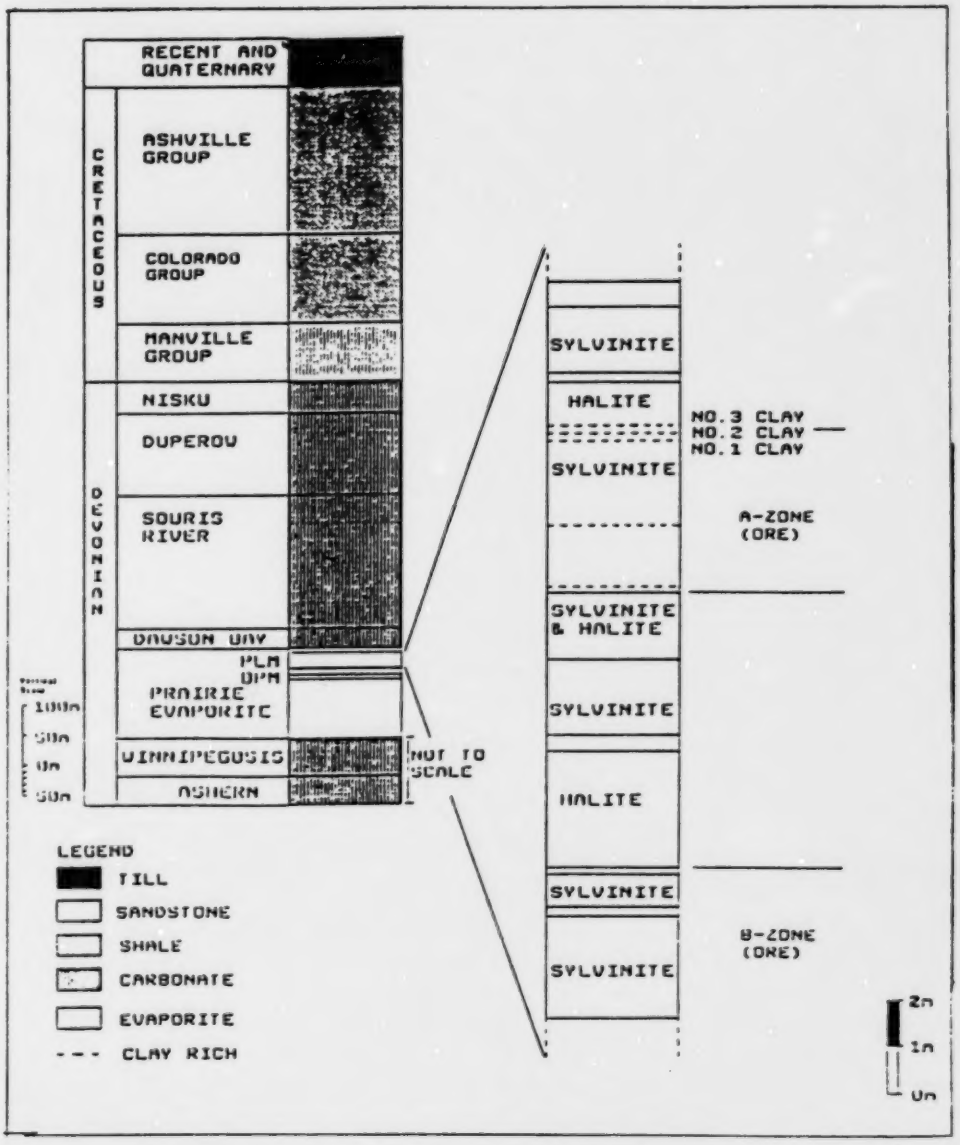

Figure 2.2 A stratigraphic section of Saskatchewan from the present surface to Devonian formations showing a detailed section of the ore horizon at the Cory mine. PLM indicates Patience Lake Member, BPM indicates Belle Plain Member (from Wittrup et al, 1997, Boys et al, 1996).

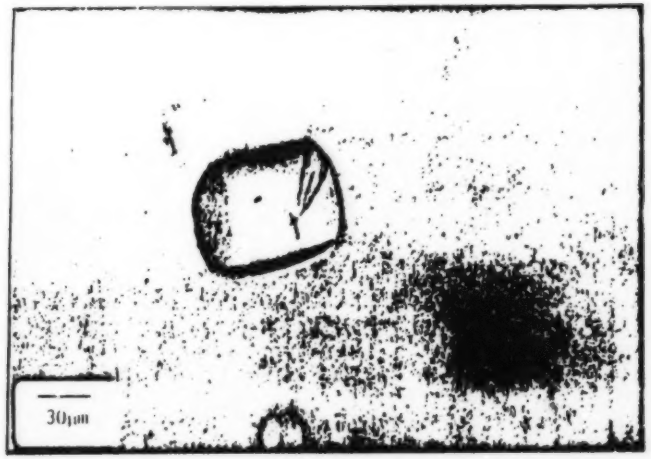

Figure 3.3 Microphotographs of inclusions in halite: (a) single phase fluid inclusion in a chevron - texture halite, (b) : two phase fluid inclusion with a salt daughter, (c) : two phase fluid inclusion with a salt daughter and latha of gypsum.

um and usually occur in chevron-texture cloudy halite crystals. Two phase inclusions are up to and larger than 100um and are evenly distributed throughout clear halite crystals. Dissolution of the carbonate or sulfate minerals could not be achieved at reasonable temperatures (<100°C) and in conjunction with inconsistent phase ratios, indicate that these minerals were trapped as solid phases.

The temperatures at which fluid inclusions in the halites homogenize range from 25°C to 70°C (fig. 2.4, table 1). Within single halite crystals less than 2 cm wide, temperatures of homogenization (T_h) can vary by as much as 30°C, the extreme case being clear halite crystals containing secondary fluid inclusions which have overgrown chevron-texture halite. This variation in temperature and texture is most likely the result of recrystallization.

All temperatures of homogenization are above room temperature even though some inclusions initially contain only brine. Precipitation of a solid phase requires the nucleation of a critical number of solute molecules but in fluid inclusions, where the number of molecules is small, supersaturation is more likely to occur. Large volume changes are required to affect a change in the solubility of salt and since liquids are relatively incompressible under the pressures created by heating the inclusions, pressure corrections for trapping temperatures are not required. A fluid moving through the salt would be saturated with halite unless it were moving through fractures which is not the case for fluids trapped in halite. For these reasons, the temperatures of homogenization of the fluid inclusions are similar to their trapping temperatures.

The distribution of homogenization temperatures of fluid inclusions in the halite is bimodal, with one population between 34°C and 44°C and the other between 46°C and 70°C with a possible division in the higher temperature populations at 54°C (fig. 2.4). The lower temperature range includes the single phase inclusions which occur along growth zones almost exclusively in the chevron- texture halites. The large range of homogenization temperatures in the chevron-texture halites makes it unlikely that these temperatures reflect those at surface when the deposit formed. Some of the apparent secondary inclusions overlap the temperatures found for the inclusions in chevron-texture halites probably because isolated inclusions can also form as primary inclusions in halite. If the inclusions that occur in chevron- texture halites do represent fluids near the surface when the evaporite deposits originally formed, the hydrogen and oxygen isotopic composition of these fluids indicate that Devonian seawater could not have been involved. As will be discussed, the isotopic compositions imply that either formation waters or meteoric waters produced the chevron texture. The

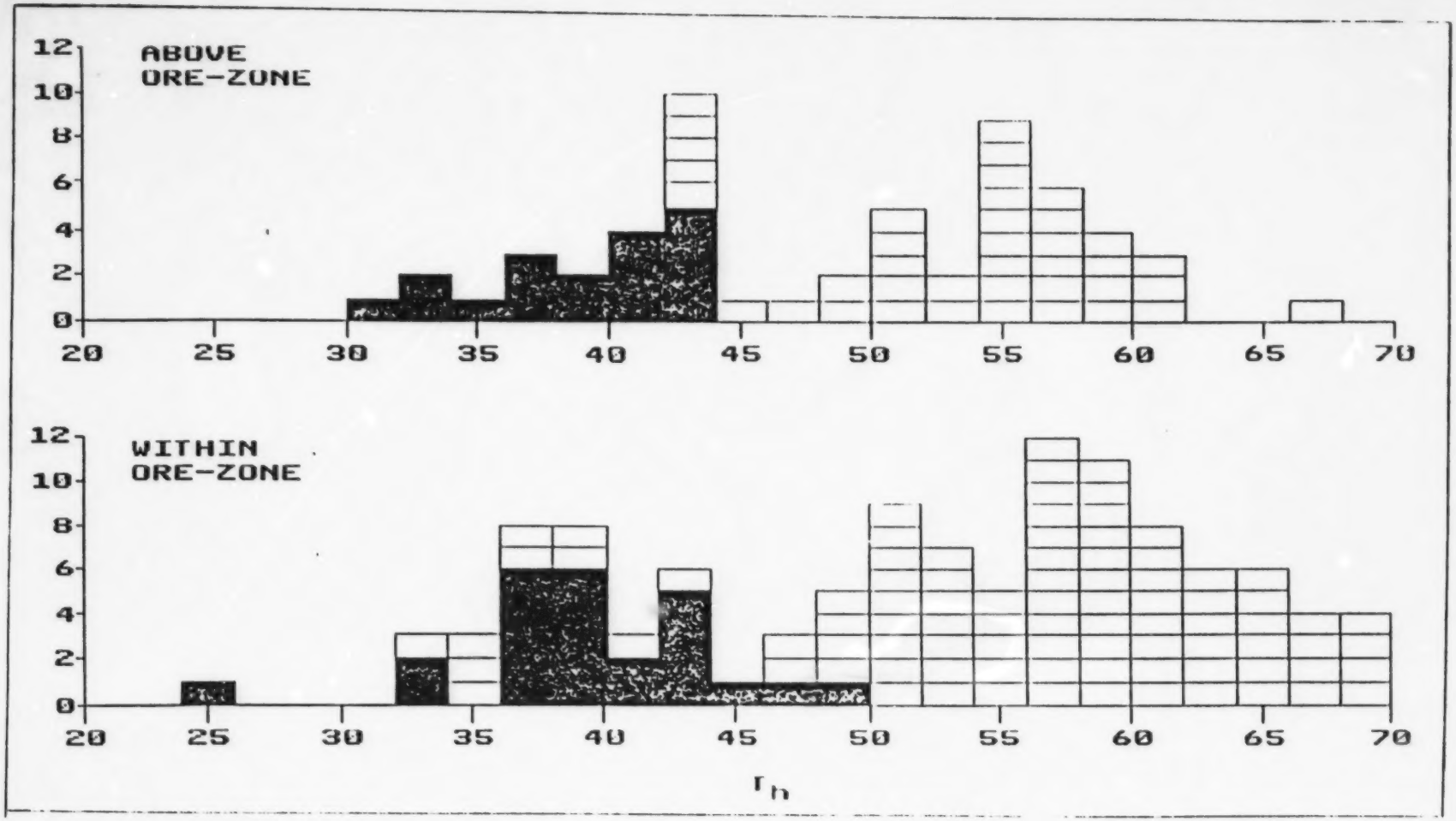

Figure 2.4 Histogram of temperature of homogenization (T_h) for "primary" chevron-texture halite (average temperature is 38°C) and for "secondary" clear halite (averages at 51°C and 57°C). Samples are from the mining face at the PCS Cory mine as described in Table 2.1.

higher average temperature of 57°C for secondary inclusions requires their formation at depth. Because the only increase in temperature that the Prairie Evaporite Formation experienced was due to burial, the trapping temperatures can be correlated with depth of burial. For an average geothermal gradient of 30°C/km, the high temperature of homogenization of the secondary fluid inclusions would require a depth of burial of approximately 1 to 2 km.

Homogenization temperatures of both primary and secondary fluid inclusions do not vary regularly with stratigraphic position (fig. 2.5) as they should if the inclusions were formed as primary depositional features. Facies within the section alternates between halite and sylvite (fig. 2.2). Halite that precipitates during sylvite facies deposition should trap inclusions that represent higher temperatures, because of solar heating and the higher enthalpy of formation of sylvite, than those precipitated during halite facies precipitation. Further, the higher degree of evaporation during sylvite deposition also should produce a regular variation in the stable isotopic composition of the halite fluid inclusion waters between halite and sylvite facies deposition (fig. 2.6). Because neither the temperature of homogenization of the fluid inclusions nor the stable isotopic composition of the water in the inclusions varies regularly with halite and sylvite facies deposition indicates that the present Prairie Evaporite does not preserve a primary depositional sequence.

Many of the formations above the Prairie Evaporite Formation are major aquifers today and probably also were in the past. Over time, connate waters would have been flushed or mixed with meteoric water affording access to the soluble salts of the Prairie Evaporite Formation by formation waters and resulting in recrystallization of the salt. The stable isotopic composition of water within formations above the Prairie Evaporite form the trend depicted in figure 2.7 (Wittrup et al, 1987), which is similar to the trend of the fluids trapped in the halite. The isotopic composition of waters from halite fluid inclusions are unlike those expected for original evaporated seawater and indicate that all salts, including the chevron-texture halite of the Patience Lake Member, have experienced recrystallization by water from formations above the Prairie Evaporite Formation (fig. 2.7).

The relation between the trapping temperature and del D values of the inclusions from halites in the Cory mine suggest three crystallization events (fig. 2.8). The lowest temperature event is recorded by the chevron-texture halite and corresponds to a depth of burial of less than 1 km and waters similar to

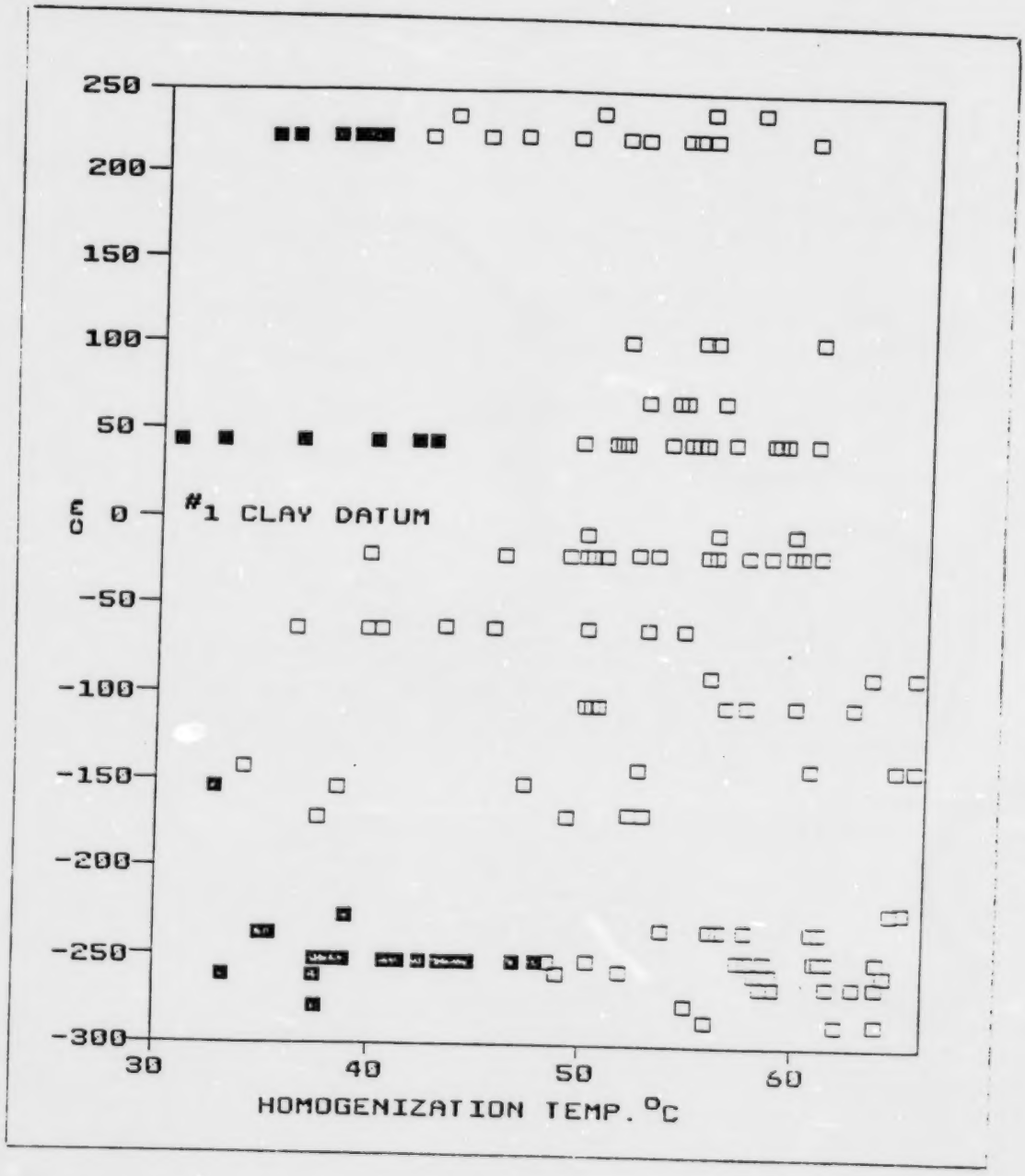

Figure 2.5 Variation in the trapping temperature of the fluid inclusions with changes between halite facies (above the #1 clay datum) and sylvite facies (A-zone) deposition. Regular variations are expected for a primary sequence. ■chevron , □ non-chevron .

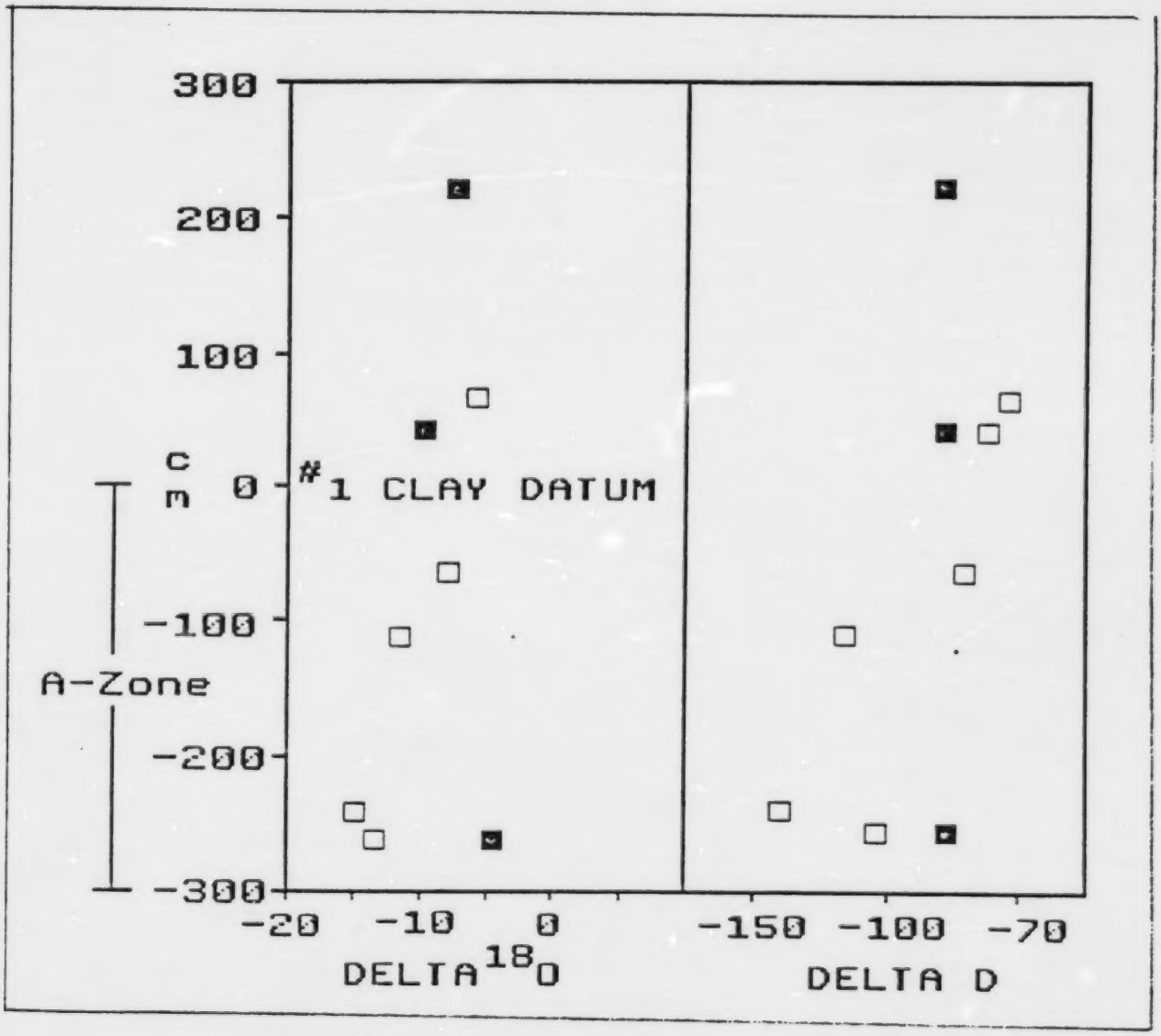

Figure 2.6 Changes in the del ^{18}O and del D values of inclusion waters in halite within the halite (above the #1 clay datum) and sylvite (A-zone) facies. Because halite and sylvite facies deposition require different degrees of evaporation, variations in the stable isotopic composition of the inclusion waters should be produced. The lack of any variation indicates that the sequence is not primary and has been recrystallized. ■chevron ,□non- chevron .

those presently in the Devonian Souris River Formation (fig 7). These results indicate that chevron textures only require high water to rock ratios to form rather than forming only at the surface. A second event occurred at higher temperatures of about 50°C corresponding to approximately 1.5 km depth with recrystallization by water with del D values near to -70, similar to those presently in the Dawson Bay Formation. The third event occurred at a slightly higher temperature of 60°C which indicates a depth of burial of approximately 2 km and waters isotopically distinct from the previous events. Since only about 1 km of cover exists at present, this later event probably occurred at maximum burial, near the end of the Cretaceous Period. Waters associated with this recrystallization event have isotopic compositions that originated from much nearer the surface and are similar to meteoric water from high latitudes. These series of events perhaps can be seen as correlating with depth of burial and time, with the shallowest, lowest temperature event recorded by the chevron-texture halites as the oldest recrystallization and the deepest, highest temperature event reflecting the most recent recrystallization.

3.5 Conclusions

Although textural evidence for primary salt exists, the stable isotopic composition of the included waters can not be modified Devonian seawater. No systematic changes in the del ^{18}O, del D or T_h of fluid inclusions occur between halite and sylvite facies deposition indicating that the deposit is not a primary sequence. Recrystallization has occurred at depths of as much as 2 km, probably at the maximum depth of burial of the deposit which occurred near the end of the Cretaceous Period. Older events, including recrystallization at shallower depths, are also recorded in the halites. The waters involved in all cases are similar to formation waters presently above the Prairie Evaporite Formation.

3.6 Acknowledgements

The authors would like to thank the Potash Corporation of

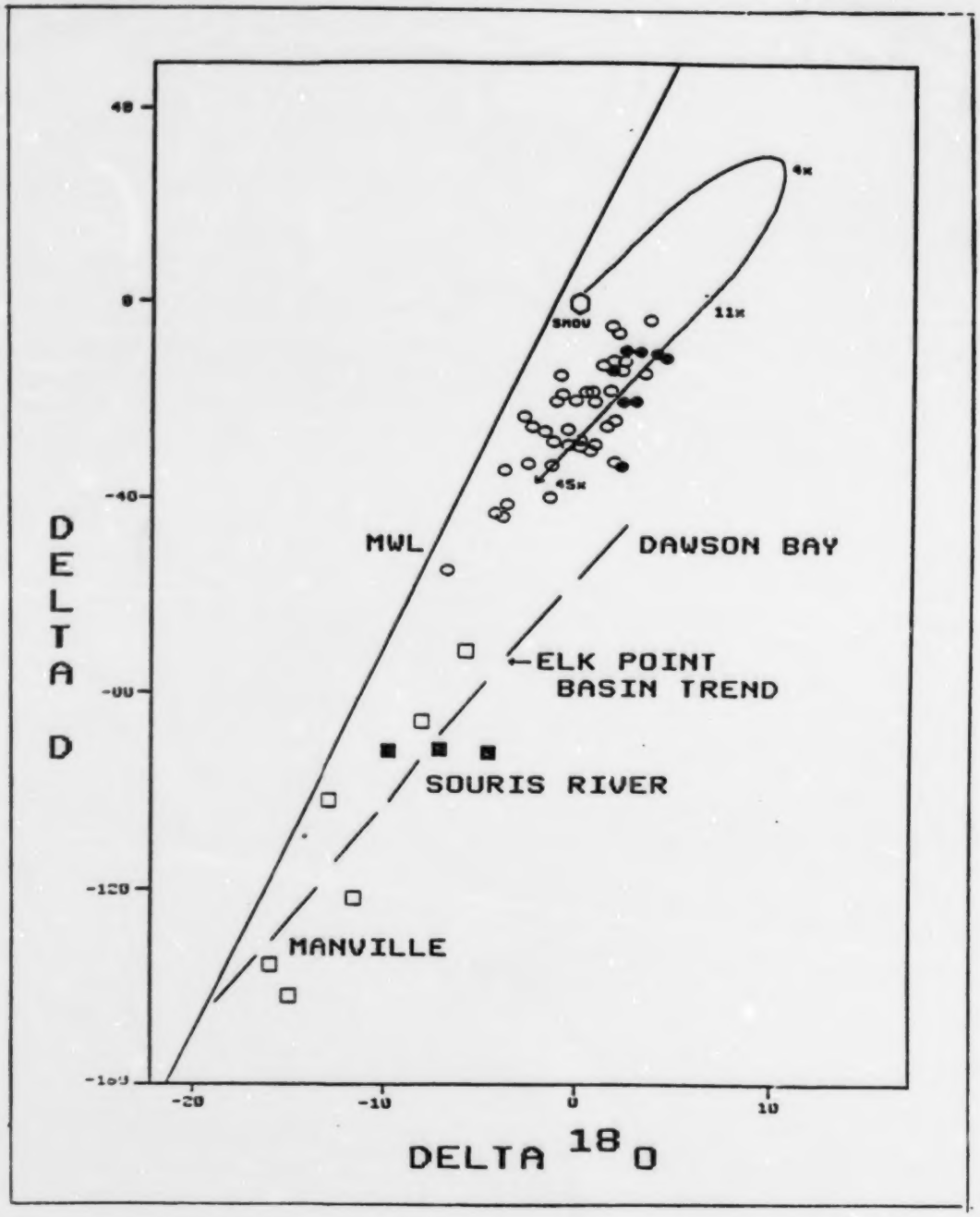

Figure 2.7 Stable isotopic composition of fluids likely to be involved in recrystallizing the halite. The natural variation in the del D and del ^{18}O composition of precipitation with latitude produces the meteoric water line (MWL). Water samples collected from formations above the Prairie Evaporite Formation form the present Elk Point Basin trend (Wittrup, et al, 1986), and work by Knauth and Beeunas (1986) with Permian salt shows the trend followed by evaporating seawater (SMOW) with halite beginning to precipitate at an evaporation ratio of 11x and sylvite at 63x. The isotopic composition of the waters extracted from the halite fluid inclusions of the Prairie Evaporite Formation reflect a source which is not evolved seawater but similar to waters forming the Elk Point Basin trend. •chevron. ○non-chevron inclusions in Permian halite; ■chevron. □non-chevron inclusions in Prairie Evaporite halite.

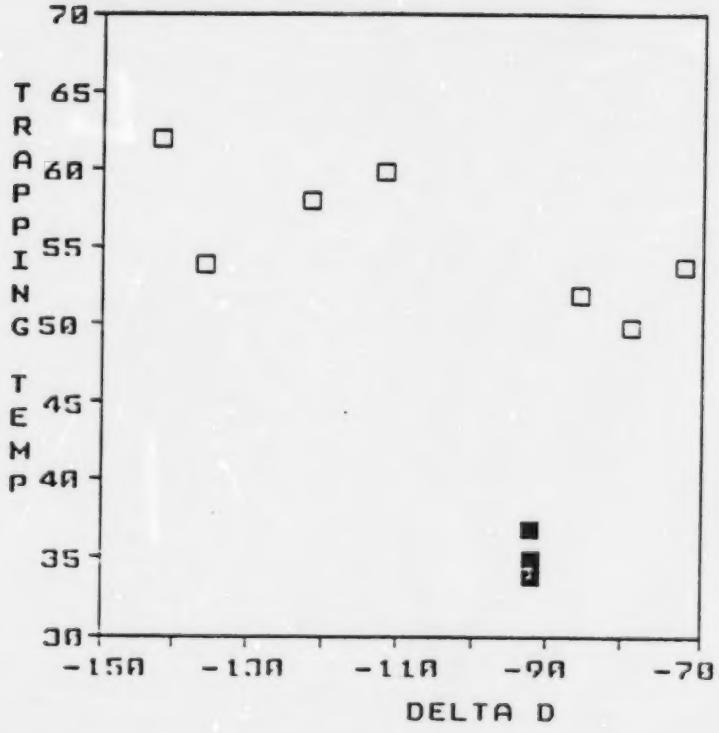

Figure 2.8 The trapping temperature of the fluid inclusions is a measure of depth of burial and the stable isotopic composition of the inclusion water is a reflection of its source. The variation in the del D and T_h indicates that at least three different waters have been involved in recrystallizing the salt at different times.

SAMPLE NUMBER	ELEVATION REL. No.1 CLAY DATUM cm	TEMP. SALT DISSOLUTION °C	AVG. TEMP. °C	WT % WATER	δD SMOW	$\delta^{18}O$ SMOW
0.5 SECONDARY	-254	56 - 64	60	1.34	-112	-14
14.1 PRIMARY	+42	30 - 38	34	1.73	-92	-10
4.1 SECONDARY	+42	42 - 59	50	.75	-79	n/a
0.6 SECONDARY	-242	56 - 68	62	.45	-142	-15
4.12 PRIMARY	+221	30 - 44	37	8.46	-92	-7
15.3 PRIMARY	-259	30 - 40	35	2.34	-92	-5
5.3 SECONDARY	-259	48 - 60	54	.22	-136	-16
.14 SECONDARY	-65	50 - 55	52	.31	-86	-8
4.2 SECONDARY	+65	52 - 56	54	.37	-72	-6
.17 SECONDARY	-107	50 - 67	58	.20	-122	-12

Table 2.1. Sample locations relative to the #1 clay seam (fig. 2.2) and homogenization temperatures and stable isotopic compositions of fluid inclusions in halite from the mining face of the Cory mine. Sample numbers indicate whether halite is chevron (primary) or clear (secondary).

Saskatchewan Mining Limited for its continued funding and valuable discussions with staff geologists. In addition, the authors would like to acknowledge the funding provided by Sask Energy and Minerals and CANMET through the Canada/Saskatchewan Mineral Development Agreement to Dr. F. Langford and Don Chipley; and the funding provided from NSERC to T. K. Kyser. Many of the ideas in this manuscript were possible only through discussions with Dr. F. Langford and Chris Boys. Members of The Saskatchewan Potash Producers Association kindly provided access to their mines and support through their discussions.

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Chapter 4

Diagenesis and Aquifer Properties of the Dawson Bay Formation

by

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4.1 Introduction

This project involves the close examination of the porosity and analysis of the cements within the Dawson Bay Formation to try and interpret its diagenetic history, and to discover the development and nature of its porosity and permiability.

The flooding in the potash mines in the Prairie Evaporite Formation of Saskatchewan, has sparked an interest in the overlying formation of the Dawson Bay, because it appears to be the source of most of the flood waters. Thus a close examination of the Dawson Bay Formation is essential to try and pinpoint where these waters are coming from and how they can be stopped.

The only other detailed work on the Dawson Bay Formation has been done by Dunn (1982) (1975, 1976, 1980, 1982) where he concentrates on this project area specifically. Dunn uses his own terminology for the members within the Dawson Bay Formation which are different than the divisions previously made. He divides the formation into four members (in ascending order): Second Red Bed Member, Burr Member, Neely Member and the Hubbard Evaporite Member (where present).

4.2 Evolution of the Williston Basin

The Dawson Bay Formation in Saskatchewan is preserved as part of the sedimentary package in the Western Canada Sedimentary Basin and the northwest segment of the Williston Basin. The Williston Basin is the southern lobe of the Devonian Elk Point Basin.

The Phanerozoic sedimentary rocks in Saskatchewan can be divided into the Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas sequences which are separated by major unconformities (Caldwell, 1986). The Dawson Bay is part of the Kaskaskian stratigraphic sequence which encompasses the Devonian and Mississippian epochs. Each of the sequences represents a major transgressive-regressive megacycle (Porter, et al, 1982).

The Williston Basin is bounded by a discontinuous ring of intracratonic arches and, during most of the Phaneorzoic time, it behaved as a gently-subsiding trough that was subcircular in outline (Caldwell, 1986).

It was not until the end of the early Ordovician that the Williston Basin formed, as evident in the Tippecanoe (Middle Ordovician to Upper Silurian) sediments (Caldwell, op. cit.). This sequence is dominated by shallow water, shelf carbonates, now preserved as dolomites and partially-dolomitized limestones such as those of the Bighorn and Interlake Groups.

Major drops in the global sea-level drop occurred at the end of early Ordovician and the beginning of the early Devonian epochs. During most of early Devonian, the Williston Basin was above sea level but by mid-Devonian time, the sea had transgressed from northern Alberta, southeastward through Saskatchewan into North Dakota. The relief that existed during pre-Kaskaskia times resulted in the new middle Devonian sea invading the Williston Basin from northwest rather than from the west as had been the case with the preceding seas (Porter et al., 1982).

The Kaskaskian sequence (Middle Devonian to Upper Mississippian time) consists of carbonate-bank deposits of the Winnipegosis Formation which succeed the thin, red and grey dolomites and shales of the Ashern Formation. The Winnipegosis Formation is overlain by the thick salt deposits of the Prairie

Evaporite Formation. During this time, the northwest margin of this basin was controlled by a massive reef complex the Presqu'ile barrier, that limited the southern encroachment of normal marine deposition. This permitted the precipitation of the economically important, potash-bearing evaporites throughout most of southern Saskatchewan (Caldwell, 1986; Fuzesy, 1983). Subsequent, localized dissolution of the evaporites by meteoric waters, resulted in collapse structures within the Western Canada Basin which affected the thickness of the overlying beds, such as the Dawson Bay Formation and the Souris River Formation of Middle to Late Devonian age.

The Peace River Arch and Western Alberta Arch remained emergent and supplied sand to the transgressive Givetian deposits. There was widespread tectonic stability during most of late middle and late Devonian time. There was a late Devonian regression, followed by an early Mississippian transgression marked by a thin but widespread veneer of dark organic shale (Porter et al., 1982).

4.3 The Dawson Bay Formation

4.3.1 General Stratigraphy

The Dawson Bay Formation was first defined by Baillie (1951) as the lowest sequence of strata in the Manitoba Group. The Manitoba Group, which is middle Devonian in age, is characterized by cycles of shales and argillaceous limestones, grading up into lighter colored limestones, that in turn are overlain by a reefoid zone (Baillie, 1951). Evaporites (anhydrite, halite) commonly mark the upper boundary of the cycles. The Dawson Bay Formation represents one of the most complete cycles of the group. The sequences above the Dawson Bay Formation are also cyclical, with green and red shales at the base, grading upwards into argillaceous, fossiliferous limestone and capped by microgranular limestone (Baillie, 1955). These cycles include the Souris River, Duperow, and Nisku Formations, ranging from middle to upper Devonian in age.

Baillie first described the Dawson Bay Formation from outcrops, that are well exposed at the northwest end of Lake

Winnipegosis. Generally, the Dawson Bay Formation ranges in thickness from 30 to 60 meters (Baillie, 1953). It thins to nothing in the extreme northwest of Manitoba and thins to only red beds with sparse fauna in western Saskatchewan (Walker, 1957; Dunn, 1982). Over the eastern portion of Saskatchewan, the Dawson Bay Formation thickens because of the presence of the capping Hubbard Evaporite Member, which is absent elsewhere.

The Middle Devonian deposits are largely restricted to the central part of the Williston Basin and extend a short distance into north-central Montana, but not as far as the Little Rocky Mountains. The name, Dawson Bay Formation, is also used in the nortern United States where it exists only in the subsurface. In central Alberta, the Dawson Bay Formation is correlated with clastic deposits of the Watt Mountain Formation and in northwestern Alberta, with the Presqu'ile Formation (Dunn, 1982). The Dawson Bay Formation is underlain unconformably by the Prairie Evaporite Formation and overlain unconformably by the Souris River Formation.

In this study, Dunn's (1982) stratigraphic nomenclature will be used. His subdivisions have a wider regional application than others. He divided the Dawson Bay Formation into: the Second Red Beds, the Burr Member, the Neely Member, and the Hubbard Evaporite .

4.3.2 Detailed Stratigraphy

In the study area, the Dawson Bay Formation ranges in thickness from 56 m in the east to 31 m in the west and generally lies at a depth of 945 meters. It lies unconformably on the Prairie Evaporite Formation except where it has been dissolved where it then lies on the Winnipegosis Formation.

4.3.2.1 Second Red Beds

In the study area, the Second Red Beds average about 4 meters thick and have little lithologic variation regionally. The Second Red Beds are dolomitic mudstones, that are locally shaly. They differ from the rest of the formation because the mudstones are usually red at the base and grade into brown to grey at the top. Generally, they are poorly consolidated, except for the upper one to two meters, where they are lithified.

The X-ray diffraction scans by Dunn (1982) found that the

Second Red Beds are 50 to 90% dolomite with subsidiary quartz, anhydrite, and halite. The clay minerals, illite and kaolinite, are present in small amounts. The presence of anhydrite needles and the impregnation by halite is the result of the last passage of ion-rich waters through the sediments. Orange halite is common in fractures of the Second Red Beds

The contact between the Second Red Bed and the overlying Burr Member is unconformable and attributed to a depositional hiatus. The contact is commonly very sharp and angular, but may also exhibit a gradational contact with the evaporites. The contact generally overlain by a veneer of bituminous material, 1 mm to 2 cm thick and in some areas the bituminous material produces an oil shale.

4.3.2.2 Burr Member

The Burr Member has a regional thickness of about 20 meters in the study area. At the base, is a thin band of black argillaceous and bituminous material. Commonly, it is succeeded by 20 to 30 cm of unfossiliferous limestone with bituminous laminae, that grades into a drab olive-brown, bioturbated carbonate. There is an abrupt upward change from unfossiliferous bioturbated carbonate at the base to a crinoidal limestone with brachiopods and corals at the top. This change is easy to recognize in cores because of a marked change from grey to buff across one of the 18 hardgrounds that may be present.

These hardgrounds are abundant throughout the Burr Member. They are irregularly spaced and range from a few centimeters to several metres apart. Cumming et al., (1959), note the occurrence of numerous hardgrounds throughout the Paleozoic limestones of the Williston Basin and relates them to periodic changes in the normal circulation of marine currents, resulting in erosion and submarine lithification of the sediments.

Dunn (1982) was able to correlate some of the surfaces over the study area with a moderate degree of confidence. However, no criteria have yet been recognized to enable the distinction of one hardground from another. Some of them appear to be at the same stratigraphic level, such as the contact between the Burr and Neely Members, and another one, 4 to 6 meters above the Second Red Beds. These can be traced over several kilometers. The hardgrounds commonly change from grey beneath to buff above. Dunn (op. cit.) notes that the grey color may be the result of higher concentrations of pyrite or argillaceous material, or both. His X-ray diffraction scans were unable to detect any subtle differences.

Typically, the surfaces of the hardgrounds have burrow indentations filled with lithoclasts and organic debris (corals, brachiopods, crinoid, shells, etc.). Dunn (1982) notes that, in his scanning electron microscope photographs, the sediment below the hardgrounds were annealed before deposition of the overlying sediments, by precipitation of cryptocrystalline calcium carbonate over the grains. The hardground surface is a thin dark line and likely is composed of very fine grained pyrite.

Anhydrite occurs as secondary needles and nodules scattered throughout the member. Pyrite is also common throughout the Burr Member and is usually associated with dolomite, whereas the anhydrite needles are only present in the calcite patches. It appears that the dolomitizing fluids dissolved some anhydrite releasing SO_4^{2-} which combines with iron to form pyrite. Dolomitization is incomplete throughout this member. There is also secondary halite plugging porosity throughout.

The contact with the overlying Neely Member is unconformable and marked by a burrowed erosional surface which is well defined, and widespread across the northern part of the Williston Basin.

4.3.2.3 Neely Member

The Neely Member averages 15 to 18 metres in thickness in the study area. It is predominantly a microcrystalline to sucrosic limestone with varying degrees of dolomitization. There is abundant bituminous material throughout, occurring as wisps, wavy laminations, or bands. It has the typical corals and crinoids of the Burr Member and also contains abundant stromatoporoids and large brachiopods. Towards the top of the member, there are widespread reefoid accumulations of stromatoporoids occur (up to 5 m high). Commonly, the stromatoporoids are broken and not in their growth position. Above the stromatoporoid beds, are pelleted limestones containing ostracods and small gastropods. These are overlain by algal stromatolites or algal laminites which, in turn, are overlain by interbedded cryptocrystalline dolomites and anhydrite. The algal stromatolites or laminites commonly contain large pores and vugs, that are usually filled with halite. Gastropod shells are commonly dissolved and their mouldic porosity filled with halite.

In regions where the Hubbard Evaporites are absent, there is a transitional contact with the overlying First Red Beds of the Souris River Formation.

4.3.2.4 Hubbard Member

The Hubbard Member is a deposit of translucent white halite and has a maximum thickness of 19 m in the study area. Typically, there are thin bands of dolomite or anhydrite throughout the halite. The top of the Dawson Bay Formation is not taken at the first appearance of the Souris River Red Beds, but at the last appearance of halite.

4.4 Depositional History of the Dawson Bay Formation

During the deposition of the Dawson Bay sediments, the Williston Basin was very close to the equator, where hot dry conditions prevailed. There has been some controversy as to the location of the equator. Some of the previous reconstructions have put much of the halite- evaporite region, including the potash deposits in Saskatchewan, into a contemporary doldrum rain belt, which is unreasonable. Heckel and Witzke, (1978) place the equator so that the evaporite region occurs in the trade-wind belt, in the rain shadow of the Caledonian-Acadian mountains.

The Second Red Beds of the Dawson Bay Formation were deposited over salt beds of the Prairie Evaporite Formation with a veneer of residual dolomitic mud at the base. The marine transgression was probably from the north or east under hot arid conditions causing some erosion of the Prairie Evaporites as the waters became supersaturated with halite. Dunn (1982a) suggests that primary dolomite was forming under these conditions and was intermingled with the underlying salts before the mud veneer became thick enough to seal the salt. Because of the hypersaline conditions, no fossils are present in the Second Red Beds except for small ostracods near the top. Braun and Mathison (1986), state that ostracods are known to exist in such conditions provided water is available.

The Second Red Beds were probably deposited under near continental to intertidal conditions. They either represent the initiating phase of a transgression, or last pulse of a regression. It is believed that there was a hiatus and that sedimentation halted between the top of the Second Red Bed and the base of the Burr Member. This is inferred by the presence of

intraformational breccias at the base of the Burr Member, and also by inferred lithification of the sediments as the rate of sedimentation slowed during the hiatus. There is also an angular unconformity between the Second Red Beds and the overlying Burr Member. This may be due to salt collapse.

Sedimentation recommenced with deposition of alternating laminae of calcite and bituminous material. This may have been preceded by a slight deepening of the seas that resulted in an increase in carbonate sedimentation. Conditions became more conducive to marine life so that soft-bodied organisms burrowed and extensively churned the sediments. Conditions at this time were likely still somewhat restricted as indicated by the scarcity of fossils. There followed a major change from the almost unfossiliferous lower Burr Member to the highly fossiliferous, upper Burr sediments. The upper Burr sediments are crinoidal limestones with brachiopods and corals. This may signify more normal open marine conditions and a major transgressive pulse.

The sediments within each of the hardgrounds may indicate more restricted conditions with a decrease in sedimentation, producing a black rind over the surface. Braun and Mathison (1986) suggest that the hardgrounds in the Burr Member indicate tectonic adjustments in the Peace River Arch area. Braun and Mathison (op. cit.) suggest that the upheaval of the arch would not be confined. In the deeper waters to the north and northwest the effects would be buffered. However, in the vast, low lying, shallow-water regions of Saskatchewan the effects tend to be magnified. They feel that the many hardgrounds attest to the upward movements of the arch destabilizing the Dawson Bay sedimentation.

Braun and Mathison (op. cit.) concluded that the main surge of the waters during the deposition of the upper Burr was from the east, because some of the fossils found in this formation have been traced to the Michigan Basin. However, some ostracods and megafossils, are from the western stock. This implies that neither the Peace River Arch, nor its sediments, totally blocked the entire seaway. Without the marine influence from the east, the Dawson Bay depression likely would probably have become a highly restricted basin due to the limited influence from the north.

The boundary between the Burr and the Neely Members is unconformable and is represented by a well defined and widespread hardground (the last major one). The Neely sedimentation commenced with an influx of argillaceous lime mud and when this clastic component disappeared another diverse fauna in carbonates developed.

During Neely Member time open marine conditions prevailed with the reassertion of the classical Devonian axis, which extends from northwest to southeast in Western Canada (Braun and Mathison, op. cit.). By Neely Member time, the eastern connection was lost, or at least had little influence. Braun and Mathison (op. cit.) suggest that the Peace River Arch had lost its eminence both as a sediment source and physical barrier, so that the main marine incursion was from the north again.

The Upper Neely Member sediments show a distinctive shallowing-upward sequence from carbonates at the base grading into microbially-laminated material, with evaporites at the top. The shallowing sea restricted the fauna to ostracods and small gastropods in pelleted lime muds, and this eventually gave rise to microbial stromatolites and laminites, and finally to interbedded cryptocrystalline dolomite and anhydrites. However, in the center of the basin halite was precipitated forming the Hubbard Evaporite Member. The conditions occurring at this time have been compared to the modern sabka environments of the Persian Gulf.

Where the Hubbard Member is absent, the dolomites and anhydrites of the upper Neely Member form a transitional contact into the First Red Beds of the Souris River Formation, thus representing another marine regression and beginning of the next cyclical sequence of the Souris River Formation .

4.5 Structure

A structural map of the Dawson Bay Formation shows a gentle, regional dip of approximately 4m/km to the south and southwest. Upon this regional trend there is considerable local relief. Dunn (1982) divides the Saskatoon Potash Mining District into two broad regions: an eastern region with distinct east to northeast trending structural lows, and a western region where the structural trends are less clearly defined. West of Saskatoon is the "Rosetown low", which is a circular depression attributed to dissolution of the Prairie Evaporites.

The Dawson Bay Formation because of its uniform thickness and the uniformity of its facies has been interpreted to be a broad shallow marine shelf deposit. The present structural relief of the formation must be the result of local subsidence, after Dawson Bay deposition. Structural lows on the Dawson Bay surface coincide with a reduction in the thickness of the

underlying Prairie Evaporites. The strata in the solution sinks commonly contain breccias composed of Dawson Bay and Souris River sediments. Where Dunn (1982) noted structural lows on his map, he examined cores from those areas and often found the Prairie Evaporites to be missing or else the Dawson Bay Formation to be extensively fractured.

At the Cominco Potash Mine, a limestone block of similar composition to the lower Burr Member was found 48 m beneath the Prairie halite This block appears to have slid or fallen into a cavern produced by salt dissolution. Dunn (1982) suggests that salt dissolution was triggered by deep crustal movements that caused fractures that became a conduit for formation waters. These waters, locally dissolved the Prairie Evaporite at the contact with the Second Red Beds, then acted as an aquifer for the formation waters. Constant flushing by fresh waters could create a large cavern before creep and collapse take place. Even today, when the overlying sedimentary pile is thicker than during the time when the dissolution took place, drillers have reported lost circulation at the contact of Second Red Beds and the Prairie Evaporite suggesting that cavities are present.

Gendzwill (1978) proposed that the salt dissolution occurred at the base of the Prairie Evaporites, and suggested that water came through the Upper Winnipegosis mounds (which provides a conduit for fluids) dissolved some of the overlying Prairie Evaporite which, in turn caused subsidence of the overlying strata. Above the Winnipegosis mounds there are depressions up to 30 m deep in the overlying beds which occur above the mounds. Gendzwill suggested that the salt beds filled the cavity by creep, and their displacement would have been transmitted through the Prairie Evaporites thereby giving rise to a cavern at the top of the formation. Eventually, the Dawson Bay sediments would also collapse into the depression forming the breccias which were encountered in the Cominco Potash Mine.

Another possible explanation for some of the collapse features in the Saskatoon region is the dewatering of carnallite. As carnallite alters to sylvite, there is a release of Mg-rich waters and a volume reduction of approximately 20%. Thus a cavity could form if the water left the system. This may account for some of the more local collapse features which occur.

Several of the cores from the Dawson Bay Formation are fractured and in regions where there has been dissolution of the Prairie Evaporites fracturing in the carbonates is prevalent. These fractures are often wedged apart by the later introduction of the clear halite.

The Second Red Beds are poorly consolidated rocks making them susceptible to fracturing and wedging apart by halite,

precipitated from supersaturated brine solutions migrating upward from the underlying salts. Dunn (1982) notes that fracture patterns are dominantly near vertical and that any tectonism that has occurred has no lateral component. He attributed that cause of the fractures to subsidence of the Dawson Bay Formation strata into cavities formed by dissolution of the Prairie Evaporite. In the study area, Dunn (1982) claims that fracturing of the carbonates appears to be the rule rather than an exception. Commonly, the fractures are sealed by halite which is fortunate for the potash mines, leaving some of the areas with Dawson Bay rocks water-free.

4.6 Formation Fluids

There have been no reported hydrocarbon shows in the Dawson Bay Formation in the study area. At the top of the Second Red Beds, and in the uppermost carbonates of the Neely Member, some kerogenous matter is present. Most of the formation is not conducive to hydrocarbon accumulation. However, in the Upper Neely Member, conditions are more favourable in the carbonate banks or shallow stromatoporid reefs. Over most of the study area, porosity of the Dawson Bay strata is apparently plugged with halite.

Dunn (1982) reported that 159 drillstem tests in the study area had yielded either clean mud, salt water, or mud-cut salt water. The clean mud recoveries indicate the lack of porosity and permeability in the Neely Member.

In several of the wells, the drillstem tests show the Burr Member to be dry whereas the Neely Member is water-bearing. This is likely the result of the larger carbonate crystals resulting in better porosity and permeability.

The water-bearing zones of the Dawson Bay Formation generally trend in seismic lows that strike north northeast. These lows correspond to Prairie Evaporite salt- dissolution features which there provide channelways (having been flushed by formation waters) that remain water-bearing.

Water from the Dawson Bay Formation has seeped into the northwestern corner of the Central Canada mine at Colonsay. Recent drilling has shown that the waters are flowing along the unconformity between the Second Red Beds and the Burr Members. It is also flowing along sub-vertical fractures in the Burr

Member. The movement of the water may be the result of the release of hydrostatic stress by creep of the potash walls toward the mining galleries. Also, the contact between the Second Red Beds and the Prairie Evaporite may be a horizon of preferential flow of formation fluids whether they be regional flows or connate pockets. Often the seeps within the mines commence with a heavy flow but gradually cease and this has been attributed to pockets of connate brines.

The Mannville Group, at the base of the Cretaceous, contains many porous and permeable sands, and forms a large regional aquifer (Wittrup et al., 1987). Formation fluids between the Mannville Group and the Dawson Bay Formation may be continuous (Dunn, 1982). Producing a huge aquifer capped at the top by the Cretaceous shale and at the base by the Prairie Evaporite.

The formation fluids within the basin flow both horizontally and vertically. There is recharge of meteoric waters at the Central Montana Uplift, which occurred during the last glaciation and continues today (Wittrup et al., 1987). The fluids generally flow north to northeast. The vertical flow is controlled by fractures and collapse-structures which occur as a result of the dissolution of the underlying Prairie Evaporite.

4.7 Research Proposal

Determination of the detailed diagenetic history of an ancient carbonate is very difficult. Most of the diagenetic alterations and porosity development of shallow water carbonate sediment occur prior to deep burial because they are chemically very reactive. Once sediments come into contact with circulating meteoric waters intense diagenetic processes begin to occur. There may be dissolution of aragonite and magnesian calcites and they are eventually replaced with stable low magnesian calcites. Identification of stages of cement precipitation can be a powerful tool in ascertaining the sequence of diagenetic environments through which a limestone passed.

Continuing work will involve petrographic work which will aided with staining. Calcite can be distinguished from dolomite with a simple stain of Alizarin Red-S. Calcite and aragonite turn red where dolomite remains colorless. A solution of potassium ferricynanide will also be used. This imparts a blue

stain to Fe-rich calcites or dolomites. These results will help in an environmental interpretation of the carbonates. Since the vadose zone is an air-water system conditions are usually oxidizing so any Fe is in the ferric state (Fe+3) and can not be incorporated into the calcite structure, therefore vadose cements are generally Fe- poor. Since phreatic waters are usually reducing the Fe is in the ferrous state (Fe^{+2}) which can easily be incorporated into the calcite lattice, so generally these cements are Fe-rich. Thus with an increase of burial there is an increase in the Fe^{+2} and also in Mn^{+2}but impoverished in Sr^{+2}these can be used to determine the zone in which the cement has formed.

By looking at the cements and their textures can give certain signatures which give clues to the environment in which they formed. In the vadose zone where the water percolation in not uniform the resulting cements that are precipitated are typically irregular in their distribution. There are usually meniscus and pendant cements. In contrast to the near surface phreatic cements where the pores are always filled with water, crystals grow by intercrystalline competition. So generally the cements are well developed isopachous layers of calcite crystals around the pore walls. The phreatic zone cements are often coarser grained than the vadose cements. With further burial depth compared to the early diagenetic cements, the cements are generally mosaic calcspar. Coarse dolomite cement (saddle or baroque dolomite), characterized by curved cleavage traces and crystal faces are associated with deep burial.

Many of the cements are too fine grained to study with the light microscope so the aid of the electron microscope can be used to aid in the identification of these cements. The SEM allows a much greater depth of focus that with the light microscope. The scanning electron microscope (SEM) is very powerful when equipped with an energy dispersive analyzer. It provides mineral identification and semiquantitative chemical analysis whenever its required. The SEM can be used to determine zonations within a cement and also give spot analysis of their different chemical compositions.

Another very powerful tool used to determine complex cementation histories is a cathodoluminescence. This can be used when cement generations are not evident from transmitted light microscope. The cathodoluminescence cause the parts of crystals to luminesce which have lattice inhomogeneities or contain activator impurities, for example, Mn which causes bright luminescence or other impurities such as Fe, Ni, or co which inhibit luminescence. These defects normally relate to change in the composition or nature (eg. reducing vs oxidizing) of the precipitating solution.

4.8 References

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